Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191

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Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 & 5 (CE)	X	
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Electricite de France	54 Units	X	

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EXECUTIVE SUMMARY

The Westinghouse Owners Group (WOG) has commissioned this report to provide a consistent approach for plants to evaluate the chemical effects which may occur post-accident in containment sump fluids. The results of this evaluation are intended to provide input on the type and amounts of chemical precipitates which may form post-accident for testing of replacement sump screens. The overall issue is being driven by Generic Safety Issue (GSI) 191 and the subsequent Nuclear Regulatory Commission (NRC) Generic Letter (GL) 2004-02.

Each plant, given their plant-specific containment material concentrations, pH, and temperature post-accident, can use the enclosed information to determine the type and amounts of chemical precipitates which may form and be transported to the sump screen. In order to meet this purpose, the report discusses the following:

- Containment materials

- Rate of dissolution of materials

- Precipitate formation due to cooling and chemical reactions

- Development of a chemical model to predict dissolution and precipitate formation

- Use of particulate generator to produce representative precipitates for screen testing

Specifically, the report presents the following conclusions.

Containment Materials

The containment materials provided on the plant surveys can be divided into fifteen (15) material classes based on their chemical composition. Ten (10) of these material classes were determined to have the potential to cause chemical effects in the containment sump: aluminum, aluminum silicate, calcium silicate, carbon steel, concrete, E-glass, amorphous silica, Interam E class, mineral wool, and zinc. The basis for excluding the remaining five (5) material classes is included in Section 3.2.

Dissolution Testing

Bench testing was performed on representative containment materials from the classes above to evaluate the dissolution characteristics of these materials. Samples were taken of the dissolved solution and were analyzed for the presence of aluminum (Al), calcium (Ca), silicon (Si), magnesium (Mg), phosphorus (P), sulfur (S), iron (Fe), zinc (Zn), and titanium (Ti). The dissolved mass values obtained for the elements P, Mg, and Ti were negligible, so these elements were not considered in precipitation formation. The elements having the highest concentration were aluminum, silicon, and calcium, and these elements are the most likely to form precipitates.

Precipitation Testing

Precipitate formed in thirteen of the sixty precipitation tests performed. In 10 tests, precipitates formed after containment materials were exposed to simulated coolant and after the temperature of the coolant was reduced. The dissolved solution from the aluminum starting material formed aluminum oxyhydroxide precipitate upon cooling for the three pH values tested. The Fiber Frax, galvanized steel, and untested fiberglass at a pH of 12 formed precipitates. For a solution pH of 4, the concrete, mineral wool, and Fiber Frax formed precipitate

upon cooling. The concrete also formed precipitate at a pH of 8. These precipitates were predominately aluminum oxyhydroxide and either calcium aluminum silicate or sodium aluminum silicate. The materials tested which did not form noticeable amounts of precipitate upon cooling were carbon steel, NUKON fiberglass, Min-K, and Interam.

Precipitation occurred upon cooling of the coolant solution because the solubility of the solids precipitating from solution decreased with decreasing temperature. The solutions became supersaturated, and crystals of that phase nucleated and grew after a period of time. In most cases, the crystal growth process took place over several hours and no significant settling took place before two hours. The exception was the aluminum oxide hydroxide or aluminum oxyhydroxide precipitate that formed within the reaction vessels before any cooling took place. This precipitation was driven by supersaturation caused by rapid corrosion of aluminum in alkaline solution at elevated temperatures.

Three precipitates formed due to chemical reactions of dissolved containment materials with each other or with the coolant pH buffer. When trisodium phosphate (TSP) was added to the dissolved solutions for CalSil and concrete in order to adjust the pH to 8, phosphate precipitate formed. In the combination precipitation tests using sodium tetraborate, no additional precipitates were formed due to chemical reaction with the sodium tetraborate. Also, a precipitate believed to be sodium calcium aluminum silicate formed from the combination of fiberglass and CalSil.

None of the thirteen precipitates described above settled rapidly; thus, in a post-accident environment, the precipitates would not be expected to settle before being transported to the sump screen.

The tests from which these precipitates formed are listed in Table 5.2-5.

Chemical Model

The results of the bench testing demonstrated that the predominant chemical precipitates are aluminum oxyhydroxide, an aluminum silicate such as sodium aluminum silicate, and calcium phosphate (for plants using trisodium phosphate for pH control). The first step of the chemical model predicts both the rate of dissolution and the solubility limits for the aluminum, calcium and silicon elements at selected times after a Loss of Coolant Accident (LOCA). For the second step, all of the material dissolved into solution is conservatively assumed to form precipitate due to the limited solubility of the key chemical precipitates. Both solution concentrations of the dissolved elements and the potential mass of the three main precipitate types are calculated as a function of time.

Particulate Generator

Testing of the proof-of-principle particulate generator demonstrated that representative particulates for the precipitates formed during the bench testing and predicted using the chemical model could be successfully generated for use in sump screen head loss testing. The chemical precipitates are intended to be treated as another class of inert debris for strainer testing purposes. The particulate generator qualification testing confirmed that the quality and temperature of the water in which the particulates are generated is not critical. However, a critical parameter determined was the limitation on the concentration of particulates within the mixing tank. If large quantities of particulates are required for screen testing, the particulates may need to be prepared in multiple batches or additional mixing tanks.

1.0   REPORT OVERVIEW

The purpose of this report is to provide sufficient information for utility engineers to perform a plant-specific evaluation of potential post-accident chemical effects in containment sump fluids to support their response to GSI-191.

Section 2 of this report presents the background of the chemical effects issue, specifically outlining the Integrated Chemical Effects Test (ICET) program, and also provides the objective of this program.

Section 3 describes the scope of containment materials considered within this program and makes an effort to categorize these materials by base composition.

Section 4 contains the original test plan, STD-MC-05-15, Revision 4, "Test Plan: Bench Testing of Chemical Effects Supporting the Evaluation of Replacement Containment Sump Screen Designs" revised to reflect the testing performed.

Section 5 documents the bench testing performed in support of this program. The selection based on actual plant conditions of the testing parameters such as temperature and pH is discussed along with the containment materials tested. The functional requirements for the testing equipment and the test procedures for the dissolution and precipitation bench testing are presented. Also, the results of the tests performed are given.

Section 6 presents the chemical model developed from the results of the bench testing described in Section 5. The model predicts the type and amount of dissolved material based on the material concentrations input and the resulting precipitates from both cooling of and chemical reactions within the sump solution. The predicted quantity and types of precipitates formed is intended for use in plant-specific sump screen testing.

Section 7 describes the particulate generator to be used to generate the precipitates formed due to chemical effects in the containment sump post-accident for screen testing. This section includes a description of the proof-of-principle particulate generator and the qualification testing performed with this apparatus.

Section 8 presents directives for plant-specific application of this report. The first section describes the intended method of implementation of the WOG bench testing results for screen vendor testing of chemical precipitates. The second section provides directions for use of the chemical model presented in Section 6 for utilities to perform their plant-specific evaluation.

Four appendices are provided to support this report. The first two contain the detailed results gathered from the dissolution and precipitation bench testing. The third contains the test data from the follow-on precipitate filterability tests. The fourth appendix presents the detailed evaluations performed in the chemical model Excel spreadsheet.

2.0 INTRODUCTION

2.1 BACKGROUND

Pressurized Water Reactor (PWR) containment buildings are designed to both contain radioactive materials releases and facilitate core cooling in the event of a Loss of Coolant Accident (LOCA). The cooling process requires water discharged from the break and containment spray to be collected in a sump for recirculation by the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS). Typically, a containment sump contains one or more screens in series that protect the components of the ECCS and CSS from debris that could be washed into the sump. Debris generated by the action of the discharged water and the latent containment debris inside containment may be transported to the containment sump when the ECCS and CSS are realigned from injecting water from the Refueling or Borated Water Storage Tank (RWST or BWST). There is a high level of concern that this debris may form a debris bed at the sump screen that would sufficiently impede the recirculating flow as to challenge long-term core cooling requirements.

The NRC identified its concern regarding maintaining adequate long-term core cooling in Generic Safety Issue (GSI) 191. Generic Letter (GL) 2004-02, issued in September 2004, identified actions that utilities must take to address the sump blockage issue. The NRC's position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculation pumps, will not impede flow through the ECCS and CSS, and will not adversely affect the long-term operation of either the ECCS or the CSS. Generic Letter 2004-02 also identifies that all mitigating actions by plants be implemented by the end of December 2007 if required to enable licensees to demonstrate acceptable ECCS and CSS performance.

A major concern in evaluating the effects of the debris transported to the sump screen after a LOCA is the chemical products which may form in a post-LOCA sump environment. Materials present in containment may dissolve or corrode when exposed to the reactor coolant and spray solutions. This behavior would result in oxide particulate corrosion products and the potential for the formation of precipitates due to changes in temperature and reactions with other dissolved materials. These chemical products may become another source of debris loading to be considered in sump screen performance and downstream effects.

2.2 INTEGRATED CHEMICAL EFFECTS TEST PROGRAM

The Integrated Chemical Effects Test (ICET) program (Reference 2.2-1) was sponsored jointly by the U.S. NRC and the nuclear utility industry, undertaken through the Memorandum of Understanding on Cooperative Nuclear Safety between NRC and the Electric Power Research Institute (EPRI), Addendum on Integral Chemical Effects Testing for PWR ECCS Recirculation. The ICET project simulated the chemical environment present inside a containment sump pool post-LOCA and monitored the chemical system for an extended period of time to identify the composition and physical characteristics of any chemical products formed during the test. The ICE test series was conducted by Los Alamos National Laboratory at the University of New Mexico with the assistance of the civil engineering department.

The objective of the ICET program was to determine, characterize, and quantify the chemical reaction products that may develop in a representative post-LOCA containment sump environment. The ICET program used five (5) test runs to study the long-term chemical reactions that may occur post-accident in a containment sump pool. The tests were representative of plants having one of three (3) buffer agents and two (2) types of insulation mixes. The buffer agents tested included all of the agents used in US PWRs. The insulation types were selected on the basis that these materials would be the primary debris materials added to the containment sump pool post-accident due to their extensive use inside containment. The test parameters (buffer agents and insulation mixes) are summarized in the following table.

Table 2.2-1: ICET Parameter Summary

Buffer Agent	Insulation Mix	
	100% Fiberglass	80% Calcium Silicate and 20% Fiberglass
Sodium Hydroxide	Test 1	Test 4
Trisodium Phosphate	Test 2	Test 3
Sodium Tetraborate	Test 5	

The ICE test parameters were defined prior to the availability of plant-specific debris generation and transport calculations performed in support of responding to GL 2004-02 (Reference 2.2-2). Thus a conservative approach was taken to estimate the amount of insulation debris that might be available to react post-accident inside a reactor containment building. Therefore, the amount of reactants (insulation debris) simulated in the ICE tests may be overly conservative relative to the amounts of reactants predicted to be available in operating PWRs.

Final data reports have been issued for four (4) of the five (5) ICE tests (References 2.2-3 - 2.2-6) as of this report. The data report for the fifth test has been reviewed and is currently undergoing comment resolution prior to publication. The NRC plans to publish an ICET program report as a nuclear regulatory guide (NUREG) document in the first quarter of 2006.

2.2.1 References

2.2-1 "Test Plan: Characterization of Chemical and Corrosion Effects Potentially Occurring Inside a PWR Containment Following a LOCA," Revision 13, July 20, 2005.

2.2-2 NRC Generic Letter 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation During Design Basis Accidents at Pressurized-Water Reactors, September 13, 2004.

2.2-3 LA-UR-05-0124, Integrated Chemical Effects Test Project: Test #1 Data Report, June 2005.

2.2-4 LA-UR-05-6146, Integrated Chemical Effects Test Project: Test #2 Data Report, September 2005.

2.2-5 LA-UR-05-6996, Integrated Chemical Effects Test Project: Test #3 Data Report, October 2005.

2.2-6 LA-UR-05-8735, Integrated Chemical Effects Test Project: Test #4 Data Report, November 2005.

2.3 PROGRAM OBJECTIVE

The objective of this program is to supplement and augment information obtained from the ICET program in order to provide information needed by plants to properly assess the potential for sump screen blockage by chemical precipitates. This information will be utilized by plants in submittals to the NRC to resolve safety issues identified in GSI-191 and further defined in GL 2004-2.

2.4 WOG CHEMICAL EFFECTS TEST PROGRAM

Specifically, more representative values of the following parameters were used:

1. Types of insulation: mineral wool, min-k, and other lesser-used insulations that were not evaluated in the ICET program were tested for post-accident chemical effects.

2. Amount of insulation: debris generation calculations, not available when the ICE test plan was generated, were used to guide the selection of appropriate quantities of debris to be used in the testing.

3. Temperature effects: the ICE tests evaluated long-term chemical effects by maintaining a constant temperature of 140°F. This test program evaluated chemical effects at sump water conditions representative of early in the transient (within 30 minutes of the postulated break). Using conservative licensing-basis assumptions, sump liquid temperatures are calculated to reach values of up to about 265°F during this 20-40 minute period.

Additional values taken from recent analytical work performed to support responses to GL 2004-02 will be used, when available and appropriate, to guide the selection of test parameters.

The tests performed in support of this program did not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials were used to select a number of tests that target the chemical reactions expected to generate the most precipitate. The selection of materials was based on the amount of material that may react and the reaction capability of the material. A technical basis for not including certain materials in the program (i.e., known reactions, minute quantities, etc.) follows in Section 3.2.

3.0 CONTAINMENT MATERIALS

In order to select the materials and their representative amounts for the bench testing, plant surveys were collected delineating the types and quantities of material present in containment. These materials include both hot-dipped and electroplated galvanized steel, untopcoated zinc coating, aluminum, copper, copper-nickel alloy, carbon steel, exposed concrete surface, fiberglass insulation, calcium silicate insulation, and other types of insulation. The minimum recirculation water volume was also obtained in order to determine the maximum ratio of material to sump volume for testing. Surveys were received and incorporated into the program for all of the sixty-nine (69) PWR plants.

3.1 COMPREHENSIVE LIST OF CONTAINMENT MATERIALS

Table 3.1-1 presents all the materials listed on the plant survey responses as being either exposed to the spray solution or submerged in the containment sump pool post-LOCA. The maximum plant ratios of material amount to minimum recirculation water volume were obtained from the plant surveys and are presented for each material. Also, the number of plants with each material and buffering agent combination as determined from the survey responses is included in the table.

Table 3.1-1: PWR Containment Materials and Associated Buffering Agents

Containment Materials		Number of Plants with Material	Maximum Material to Recirculation Water Volume Ratio	Number of Plants with Material – Buffering Agent Combination		
				Trisodium Phosphate	Sodium Hydroxide	Sodium Tetraborate
Metals	Aluminum	69	5.42 ft²/ft³	29	29	11
	Carbon Steel	55	10.78 ft²/ft³	25	23	7.
	Copper	65	11.11 ft²/ft³	27	27	11
	Galvanized Steel	69	19.47 ft²/ft³	29	29	11
	Untopcoated Zinc Coating	62	27.98 ft²/ft³	27	24	11
Concrete	Concrete	62	4.79 ft²/ft³	28	27	7
Insulation	3M Interam	2	2.8E-4 ft³/ft³	2	0	0
	3M-M20C	1	2.5E-4 ft³/ft³	0	0	1
	Armaflex / Anti-sweat rubber / Foam rubber	8	2.6E-4 ft³/ft³	4	4	0
	Asbestos	6	0.01 ft³/ft³	0	6	0
	Benelex 401	1	3.8E-4 ft³/ft³	0	1	0
	Calcium Silicate	28	0.18 ft³/ft³	8	16	4
	Cerablanket	2	1.1E-4 ft³/ft³	0	2	0
	CP-10	1	1.0E-4 ft³/ft³	0	1	0
	Fiberglass Fiber	61	0.23 ft³/ft³	27	28	6
	Foamglas	3	5.4E-3 ft³/ft³	2	1	0
	Kaowool	6	0.02 ft³/ft³	2	4	0
	Kaylo	1	3.9E-3 ft³/ft³	0	1	0

Containment Materials		Number of Plants with Material	Maximum Material to Recirculation Water Volume Ratio	Number of Plants with Material – Buffering Agent Combination		
				Trisodium Phosphate	Sodium Hydroxide	Sodium Tetraborate
Insulation Continued	Leadwool	2	2.4E-4 ft³/ft³	2	0	0
	Marinite	6	1.2E-3 ft³/ft³	0	4	2
	Mat-Ceramic	1	2.9E-5 ft³/ft³	0	1	0
	Microtherm	13	5.5E-4 ft³/ft³	6	2	5
	Mineral Fiber	1	7.5E-3 ft³/ft³	1	0	0
	Min-K	15	1.3E-3 ft³/ft³	6	6	3
	Mineral Wool / MinWool	11	0.04 ft³/ft³	4	7	0
	Mudd	2	8.6E-4 ft³/ft³	0	0	2
	PAROC Mineral Wool	2	5.6E-4 ft³/ft³	0	2	0
	Tempmat	7	5.1E-3 ft³/ft³	0	7	0
	Thermal Wrap	7	0.03 ft³/ft³	0	3	4
	Thermolag 330-1	5	9.4E-5 ft³/ft³	4	1	0
	Transite	1	1.9E-3 ft³/ft³	0	1	0
	Unibestos	1	1.4E-3 ft³/ft³	0	1	0
	Vinylcel	1	Not provided	1	0	0

3.2   CLASSIFICATION OF CONTAINMENT MATERIALS

The base chemical composition of each containment material was determined from published information, including information from product data sheets, material safety data sheets, vendor web sites and text books. For natural products such as asbestos and vermiculite, nominal composition data were used. The data were tabulated in Table 3.2-1 and were used to establish general classifications of the materials. These classifications are discussed in this section and are summarized in Table 3.2-2.

Aluminum

This classification includes all aluminum alloys. Aluminum is primarily present as structural members, coatings, small components (e.g., valves) and thin foil coatings on insulation. Commercially pure aluminum (SA 1100) was used for bench-scale dissolution testing. This approach is considered to be conservative since aluminum alloys are typically more corrosion resistant than pure aluminum[1].

Aluminum Silicate

This classification includes both synthetic aluminum silicate insulation materials and natural aluminum silicates such as kaolin clay and vermiculite. The containment materials represented in this classification are 3M M-20C insulation[2,3], 3M I-Series insulation[3,4], Cerablanket[5], Fiber Frax Durablanket[6], Kaowool[5], Mat-Ceramic insulation[5], mineral fiber[3,7], and PAROC mineral wool[8]. Fiber Frax Durablanket was used in bench-scale dissolution testing to represent this material class.

Calcium Silicate

This classification includes low-density calcium silicate mat insulation, asbestos and asbestos-containing insulation, and the high density refractory materials (e.g., transite). The containment materials represented in this classification are asbestos, Cal-Sil insulation[9], Kaylo[10], marinite[11], Mudd[12], transite[13], and Unibestos[14]. Low-density calcium silicate was used in bench-scale dissolution testing to represent this material class.

Asbestos is a broad classification of naturally-occurring minerals that are primarily mixed metal silicates[15]. Most forms of asbestos are typically resistant to dissolution under a broad pH range. To bound all asbestos materials, it was assumed that all asbestos is chrysotile (primarily magnesium silicate), and has the same dissolution behavior as calcium silicate. This conservative assumption is considered acceptable due to the low occurrence of asbestos.

Carbon Steel

This classification includes all uncoated/ungalvanized carbon and low alloy steels. These materials are typically present as structural members. Carbon steel SA 508 Class 2 was used in bench-scale dissolution testing to represent this material class. Although no steps were taken to intentionally pre-oxidize the specimens, a thin natural, low temperature oxide was present.

Concrete

Concrete is a complex mixture of cement, natural sand and gravel/rocks (all primarily silicon dioxide), and admixing agents (e.g., fly ash)[16]. Cement is prepared by heating a mixture of calcium oxide and silicate-containing materials to create tricalcium silicate and dicalcium silicate. Based on the base composition of concrete, the dissolution behavior of this material could reasonably be expected to be similar to that of calcium silicate. However, concrete was classified as a distinct material since it is ubiquitous in PWR containments. Ground concrete was used in bench-scale dissolution testing to represent this material class. The concrete sample was aged for greater than 28 days prior to use. Use of ground concrete is considered conservative due to its high surface area relative to that of structural concrete.

Copper

This classification includes all copper-containing alloys. As demonstrated in prior testing and based on published data[1], this material class is resistant to corrosion under expected post-accident conditions. Therefore, this material was not included in the current test program.

E-Glass

This classification includes all fiberglass insulation and cellular glass. E-glass is an amorphous material containing silicon dioxide, calcium oxide, aluminum oxide and boric oxide[3]. The material is typically resistant to dissolution in aqueous solutions over a broad range of temperature and pH, but some reaction does occur at high temperatures in alkaline solution. The containment materials represented in this classification are all fiberglass insulation (unspecified manufacturers), Foamglas[17], NUKON[19], Temp-Mat[21] and Thermal Wrap[22]. Unspecified fiberglass and NUKON were used in dissolution testing to represent this material class.

Amorphous Silica

Similar to the E-glass category, the amorphous silica class contains materials made up of predominately amorphous silica with a small percentage of E-glass. The containment materials in this classification are Min-K[18] and Microtherm[20]. Min-K was used in the bench-scale dissolution testing to represent this material class and was found to behave differently enough from the E-glass class to require its own class.

Interam E-Class Insulation

Interam E-Class insulation is nominally composed of a blanket of fibrous hydrated alumina and aluminum silicate, with an aluminum alloy foil outer layer[23]. No other materials were of similar composition. Therefore, this classification only includes the Interam E-Class material, and this material was included in bench-scale dissolution testing.

Mineral Wool

This classification includes mineral wools produced from steel slag and rock wools produced from naturally-occurring minerals such as basalt and dolomite[24]. Mineral wools are typically

slightly less resistant to chemical attack than rock wools[24]. Steel slag is nominally composed of calcium oxide, silicon dioxide, iron oxides, iron metal and minor amounts of other metal oxides and sulfur[7]. The containment materials represented in this classification are Min-Wool[25] and rock wool (manufacturers unspecified). Min-Wool was used in bench-scale dissolution testing to represent this material class.

Nickel

This classification includes all nickel-containing alloys. As demonstrated in prior testing, and based on published data[1], this material class is resistant to corrosion under expected post-accident conditions. Therefore, this material was not included in the current test program.

Organic Mastics

This classification includes all mastic coatings that contain inorganic materials in organic binders. The containment materials represented in this classification are CP-10 and Thermolag 330-1. The inorganic components of these compounds are encased in polymeric materials, vinyl acetate for CP-10, epoxides for Thermolag, and thus would not be exposed to sump fluids[26,27]. On this basis, these materials were not represented in bench-scale testing.

Other Organic Materials

This classification includes rubber, foam rubber, phenolic resins, pressed wood products, and liquid hydrocarbons. The containment materials represented in this classification are: Armaflex[28], Benelex 401[29], Kool-Phen[30], and RCP motor oil. Consistent with the protocols established in the ICET program, organic materials were generally excluded from bench-scale dissolution testing. The basis for excluding such materials is that they were judged to be unlikely to breakdown to produce precipitate-forming species under the temperature and chemistry conditions tested.

Reactor Coolant Oxides

This material class includes the nickel ferrite and other oxides typically present in the corrosion product film on the inner surfaces of the reactor coolant system during normal operation. Under accident conditions, a small fraction of this film may spall off or be solubilized due to oxidation of the coolant. Based on measured releases during intentional coolant oxidation routinely conducted as part of normal plant shutdown[31], the magnitude of this release is expected to introduce a negligible quantity of material into the sump under accident conditions. Therefore, this material class was not included in the current test program.

Zinc

This classification includes galvanized coating on carbon steel, including both hot-dipped and electrodeposited galvanization, and zinc coatings. Hot-dipped galvanized steel was used in bench-scale dissolution testing to represent this material class. Organic zinc coatings in which zinc is bound in an organic matrix, and therefore not exposed to the coolant, should be classified under "Other Organic Materials." Other organic zinc coatings should be treated as zinc metal.

Table 3.2-1: Base Composition of Containment Materials

Material	Composition	Notes
3M Interam E-5	70% hydrated alumina, 25% aluminum silicate, 3% metal foil (aluminum alloy), organic binders	
3M M-2O-C	50% vermiculite (aluminum and magnesium silicate + other metal silicates), 13% aluminum silicate, foil/binders	
Aluminum	aluminum	
Armaflex	nitrile rubber + PVC	
Asbestos	magnesium silicate + other metal silicates	
Benelex 401	lignocellulose hardboard (pressed wood)	
Calcium Silicate Insulation	calcium silicate	
Cerablanket	100% aluminosilicate	
Concrete	>80% silicon dioxide, 13% cement	3
CP-10	20% silica (quartz), 12% hydrated alumina, 5% titanium dioxide + vinyl acetate	
Fiberfrax Durablanket	100% aluminosilicate	
Fiberglass Fiber	>95% E-glass + <5% binders	1
Foamglas	100% E-glass	1
Kaowool	80% aluminum silicate + 20% kaolin clay (hydrated aluminum silicate)	4
Kaylo	90% calcium silicate + 10% asbestos	5
KoolPhen	phenolic resin	
Marinite	70% calcium silicate + 22% calcium metasilicate + organic fiber + fibeglass	6
Mat-Ceramic	100% aluminosilicate	
Microtherm	90% (amorphous silica + silicon carbide) + 10% (E-glass + aluminum oxide)	1
Mineral Fiber	100% aluminosilicate	
Min-K	amorphous silica + E-glass (fiberglass)	1
MinWool	steel slag + 5% phenolic resin binder	2
Mudd	>50% calcium silicate, >10% cement, 10% (silicon dioxide + aluminum oxide) + other metal oxides/silicates	
Nukon Base Wool	>95% E-glass (fiberglass) + <5% binders	1
PAROC Mineral Wool	100% aluminosilicate	

Material	Composition	Notes
Tempmat	100% E-glass fiberglass	1
Thermal Wrap	>95% E-glass (fiberglass) + <5% binders	1
Thermolag 330-1	6% silicon dioxide (quartz), 3% E-glass (fiber glass) + epoxides	
Transite	70% calcium silicate + 22% calcium metasilicate + organic fiber + fiberglass	6
Unibestos	calcium silicate + asbestos (magnesium silicate)	

Notes:

1. E-glass is nominally composed of: 52-56% silicon dioxide, 16-25% calcium oxide 12-16% aluminum oxide, 5-10% boric oxide and minor amounts of sodium oxide, potassium oxide magnesium oxide iron (III) oxide, and titanium oxide.

2. Steel slag is nominally composed of: 40-52% calcium oxide, 10-19% silicon dioxide, 7-30% iron (II) oxide, 2 10% iron (III) oxide, 5% manganese oxide, 5% magnesium oxide, and minor amounts of aluminum oxide, phosphorous pentoxide, sulfur and iron.

3. Cement is predominantly dicalcium and tricalcium silicate, with minor amounts of calcium oxide, aluminum silicate, ferroaluminum silicate and other metal silicates.

4. This material may contain minor amounts of other inert additives such as titanium dioxide.

5. Newer material may contain other silicates in place of asbestos.

6. Transite is a higher density version of marinite.

Table 3.2-2: Containment Material Classification Summary

Material Class	Materials in Class	Representative Material
Aluminum	Aluminum alloys, aluminum coatings	Aluminum (pure)
Aluminum silicate	Cerablanket, FiberFrax Durablanket, Kaowool, Mat-Ceramic, Mineral Fiber, PAROC Mineral Wool	FiberFrax Durablanket
Calcium silicate	Asbestos, Cal-Sil insulation, Kaylo, Marinite, Mudd, Transite, Unibestos	Cal-Sil Insulation
Carbon Steel	All carbon and low alloy steels	SA 508 Cl 2
Concrete	Concrete	Ground Concrete
E-glass	Fiberglass insulation, NUKON, Temp-Mat, Foamglas, Thermal Wrap	NUKON, Unspecified Fiberglass
Amorphous Silica	Min-K, Microtherm	Min-K
Interam E Class	Interam E Class	Interam E-5
Mineral wool	Min-Wool, Rock Wool	Min-Wool
Zinc	Galvanized steel, zinc coatings	Galvanized Steel
Copper	All copper alloys	None
Nickel	All nickel alloys	None
Organic Mastics	CP-10, ThermoLag 330-1	None
Other Organics	Armaflex, Kool-Phen, Benelex 401, RCP motor oil	None
Reactor Coolant Oxides	nickel ferrite and other oxides	None

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3.2-22   Product Data Sheet, SOFTR Thermal Wrap, Owings-Corning Corporation, 2005.

3.2-23   Material Safety Data Sheets, Interam E-10AE Mat, Interam E-5A, E-5A-3 and E-5A-4 Mats, and Interam E-50, 3M Corporation, 1998.

3.2-24   Bynum, R.T., Jr., Insulation Handbook, McGraw-Hill, 2001.

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4.0 TEST PLAN

4.1 INTRODUCTION

The test plan presented in this chapter was reviewed and commented upon by the nuclear industry through the Nuclear Energy Institute (NEI). An overview of the test plan was presented to the NRC at a public meeting on November 2, 2005 and comments were received both orally and in written form. The test plan was revised to incorporate industry and NRC suggestions and the final version was issued on November 22, 2005 (Reference 4.4-3).

4.1.1 Background

Pressurized Water Reactor (PWR) containment buildings are designed to both contain radioactive materials releases and facilitate core cooling in the event of a Loss of Coolant Accident (LOCA). The cooling process requires water discharged from the break and containment spray to be collected in a sump for recirculation by the Emergency Core Cooling System (ECCS) and Containment Spray System (CSS). Typically, a containment sump contains one or more screens in series that protect the components of the ECCS and CSS from debris that could be washed into the sump. Debris generated by the action of the discharged water, and the latent containment debris inside containment, may be transported to the containment sump when the ECCS and CSS are realigned from injecting water from the Refueling or Borated Water Storage Tank (RWST or BWST). There is a high level of concern that this debris may form a debris bed at the sump screen that would sufficiently impede the recirculating flow as to challenge long-term core cooling requirements.

The NRC identified its concern regarding maintaining adequate long-term core cooling in Generic Safety Issue GSI-191. Generic Letter 2004-02, issued in September 2004, identified actions that utilities must take to address the sump blockage issue (Reference 4.5-2). The NRCs position is that plants must be able to demonstrate that debris transported to the sump screen after a LOCA will not lead to unacceptable head loss for the recirculation pumps, will not impede flow through the ECCS and CSS, and will not adversely affect the long-term operation of either the ECCS or the CSS. Generic Letter GL 2004-02 also identifies that all mitigating actions by plants, if required, to enable licensees to demonstrate acceptable ECCS and CSS performance, be implemented by the end of December 2007.

4.1.2 Program Overview

As discussed below, the Integrated Chemical Effects Test (ICET) program (Reference 4.5-1) used five (5) test runs to study the long-term chemical reactions that may occur post-accident in a containment sump pool that was representative of plants having one of three (3) buffer agents and two (2) types of insulation mixes; 100% fiberglass and an 80% / 20% mix of calcium silicate and fiberglass insulations. Thus, while useful and informative, the ICET data is limited. Furthermore, as the ICET parameters were defined prior to the availability of plant-specific debris generation and transport calculations, the amount of reactants simulated in the ICE tests may be overly conservative. An assessment of the corrosion products that would be generated

with more representative debris quantities is appropriate. Thus, the goal of this program is to supplement and augment information obtained from the ICET program. The information flow associated with this program is shown schematically in Figure 4.1-1, below.

Figure 4.1-1: Schematic for Information Flow for Chemistry Effects Bench Tests

```
                    ┌─────────────────────────┐
                    │    2. Plant Data:       │
                    │ Identification of materials and │
                    │  conditions to be covered in │
                    │       bench test        │
                    └─────────────────────────┘
                                │
                                ▼
┌──────────────────┐  ┌─────────────────────────┐  ┌──────────────────────┐
│  1. ICET Test:   │  │ 3. Chemistry Bench Testing: │  │ 4. Screen Performance │
│ Basic information │→ │  Develop information on  │→ │      Testing:        │
│ on post-accident │  │ chemical products to be used │  │ "Proof of Performance" testing │
│ chemical effects │  │ with testing replacement sump │  │ performed for replacement sump │
│                  │  │ screens with plant-specific │  │       screens        │
│                  │  │     debris loading      │  │                      │
└──────────────────┘  └─────────────────────────┘  └──────────────────────┘
```

Briefly summarizing the information flow, starting from the left-hand side of Figure 4.1-1;

1. The ICE tests provide basic information on long-term post-accident sump chemical effects. That information includes the conditions and materials used in the test and the data that was collected, as well as conditions and materials not included in the ICE test and is used both as input to set the bench test conditions, and to define the plant-specific information requested of plants.

2. Using plant-specific input, specific materials and amounts of materials are selected for the bench testing.

3. The bench testing is conducted for the purpose of characterizing the type and amount of chemical products that are produced. The chemical products themselves are characterized with respect to settling.

4. This chemical product information generated from the bench testing is used as an input to performance testing to be conducted by licensees and vendors of replacement sump screens.

The merit of this approach to testing for this issue has been demonstrated in bench testing performed by Westinghouse in late September 2005. Separate effects bench tests with two simulated post-accident chemistry conditions were performed. A draft review of the results from both tests suggests that bench testing for chemical effects will provide useful and usable data to support both understanding of post-accident chemical effects and the performance testing of replacement sump screens.

The characterization of the chemical products from bench testing is also intended to support and be used in the downstream effects evaluation of chemical products on the ECCS and CSS flow path, and equipment (pumps valves, etc.) in that flow path.

4.1.3 Purpose of Bench Tests

The purpose of this test plan is to develop information to supplement and augment the information obtained from the ICET program. In five (5) tests, the ICET program examined the long-term chemical reactions, and the associated chemical reaction products, that may occur in a simulated containment sump environment using two (2) types of thermal insulation materials and three (3) buffer agents. The insulation mixes and the buffering agents studied in the ICET program are given in the table below.

Table 4.1-1: Summary of ICE Test Matrix

Thermal Insulation	Buffer Agent		
	Sodium Hydroxide	Trisodium Phosphate	Sodium Tetraborate
100% Fiberglass	ICET Test 1	ICET Test 2	ICET Test 5
80% Calcium Silicate / 20% Fiberglass	ICET Test 4	ICET Test 3	

Knowing that the number of tests to be run as part of the ICET program was limited, criteria were established to guide the selection of test parameters.

1. The selection of the insulation types and buffer agents used in the ICE test were based on industry survey information and made with the objective of testing the most dominant types of thermal insulations and buffer agents that would react in the containment sump pool post-accident.

2. The selection of the amount of insulation to be used in the test was based on early data regarding the volume of debris that would be generated from a postulated high energy line break and selected to be representative of the fleet of PWR plants licensed to operate in the US.

Thus, the ICET results are not all-inclusive of all insulation types that might be in containment, and may excessively account for insulation debris in the containment sump.

4.2 SUPPLEMENTAL CHEMISTRY EFFECTS PROGRAM

Therefore, an additional chemistry effects test program is to be performed. The purpose of this additional program is to supplement and augment the data obtained from the ICET program. Specifically, more representative values of the following parameters will be used:

1. Types of insulation; micro-therm, min-k, and other lesser-used insulations will be evaluated for post-accident chemical effects.

2. Amount of insulation; debris generation calculations, not available when the ICE test plan was generated, will be used to guide the selection of appropriate quantities of debris to be used in the testing.

3. Temperature effects; the ICE test evaluated long-term chemical effects by maintaining a constant temperature of 140 °F. This test program will evaluate chemical effects at sump water conditions representative of early (within 30 minutes of the postulated break) in the transient. Using conservative licensing-basis assumptions, sump liquid temperatures are calculated to reach values of up to about 265 °F during this 20-40 minute period.

Additional values, taken from recent analytical work performed to support responses to Generic Letter GL 2004-02 will be used, when available and appropriate, to guide the selection of test parameters.

The tests described here do not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials have been used to select a number of tests that target the chemical reactions expected to generate the most precipitate. The selection of materials is based on the amount of material that may react, and the reaction capability of the material. A technical basis for not including certain materials in the program (i.e., known reactions, minute quantities, etc.) will be prepared for those materials, and will be documented in the project report.

4.2.1 Test Approach

The tests described here will be done at the "bench level" scale. This will allow testing to be completed in a time and cost effective manner.

First, using standard techniques, the dissolution rate for each of the containment materials of interest will be measured.

1. This will be done as a function of pH and temperature.

2. Interactions between dissolved matter from the various materials to form precipitates will then be measured as well as precipitate formation upon cooling.

3. This data will be used to construct a model that will take plant specific containment material mixes and conservatively predict amounts and character of precipitates that will form for a large break LOCA.

This information is essential for subsequent testing performed to demonstrate sump screen margin in performance tests. Functional requirements will be developed for equipment that can produce the type and quantity of precipitates needed for such tests.

Additional information, taken from recent analytical work performed to support responses to Generic Letter GL 2004-02 will be used, when available and where possible, to guide the selection of test parameters.

The tests described here do not include an investigation of all possible chemical reactions of containment materials. The ICET program and the known properties of containment materials have been used to select a number of tests that target the chemical reactions expected to generate the type and quantity of precipitates most likely to affect sump screen performance.

The approach used to develop the test plan was to produce reasonable but conservative estimates for precipitate formation. Dissolution rates will be measured for each containment material individually. These rates are expected to be higher than that obtained from containment material mixtures. This is because the dissolution of one material will have either no effect or an inhibiting effect on the dissolution of other materials. For instance:

1. The results of ICET Test 4 suggest that Cal-Sil inhibits the dissolution of aluminum. However, the region of influence for some LOCAs will not include Cal-Sil, even at a plant with a large volume of Cal-Sil.

2. Similarly, trisodium phosphate may inhibit the dissolution of Cal-Sil, but the trisodium phosphate in containment will take a finite period of time to dissolve. Thus, there may be some period during which dissolution of Cal-Sil is not influenced by the presence of trisodium phosphate.

The bench testing will be performed at temperatures up to a maximum value determined from industry surveys of containment pool temperatures that are expected after a large break LOCA before recirculation. This allows reactions during the first hours of a LOCA to be considered.

Consideration of the dissolution and precipitation reactions in separate bench-scale tests simplifies the interpretation of results and enables the use of the precipitation in chemical modeling. If integrated testing was performed with complex mixtures of materials, dissolution and precipitation occur simultaneously, making weight loss and gain information minimally useful. Integrated tests, while realistic, produce complex mixtures of products that are difficult to analyze.

4.2.2 Dissolution Testing

The dissolution of each of the following materials will be measured at temperatures determined from industry surveys with a range of pH values that are experienced in the post LOCA environment.

1. The maximum pH will be 12.0 and will be generated with sodium hydroxide (NaOH). This value is slightly higher than the maximum pH expected for a plant using NaOH pH buffering.

2. An intermediate pH of 8 will be tested. This is a typical containment pool pH after complete addition of the pH buffering agent in plants using trisodium phosphate or sodium tetraborate.

3. The minimum pH will be approximately 4.1 and will be generated with 4400 ppm boric acid. This is the lowest pH expected for all plants before buffering agent addition is

completed. Although the majority of plants are bounded by a boric acid concentration of 2800 ppm, the difference in pH is small at 4.4 vs. 4.1 with 4400 ppm boric acid, and boron (as borate) is not a critical complex in key precipitation reactions. Note, the levels of acidic radiolysis products such as hydrochloric acid are not expected to be significant early in a postulated event prior to completion of buffering agent addition. After dissolution of the buffering agent, the long term generation of HCl will have little effect on pH. The large excess of the buffering agent will set the pH.

The pH values listed are starting values. The pH will vary as the containment materials dissolve.

Materials to be tested include, as a minimum:

- Aluminum sheet

- Cal-Sil insulation

- NuKon-fiberglass

- Previously untested fiberglass (Temp Mat)

- Powdered concrete

- Mineral Wool (e.g. K-Wool)

- Microporous Insulation (e.g. Kool-phen-K)

- Fire Retardant Material (e.g. FiberFrax)

Note, the material list was amended based on receipt of additional industry input. Prior to use, specimens were pretreated as required to simulate prototypical material conditions. The pretreatment methods used will be consistent with industry standards and past testing, as documented in the project report.

The total amount of material dissolved after a minimum of two and a maximum of four time periods will be measured. It is anticipated that these time periods will have the following range:

1. The short time was 30 minutes. This is generally representative of the time from the initiation of the break to initiation of realigning of the ECCS to the recirculate from ion mode from the containment sump with all trains of the ECCS operating.

2. Additional samples were taken at sixty and ninety minutes. Sixty minutes is generally representative of the time from the initiation of the break to before initiation of realigning the containment sump to recirculate from the containment sump with only one train of ECCS operating.

Trisodium Phosphate Dissolution Rate

Information was collected from literature on the dissolution rate anticipated for trisodium phosphate after a LOCA. Additional bench scale testing was not determined to be necessary.

Corrosion Products from the RCS

Nickel and iron dissolution from the RCS will not be included in this testing. Normal PWR shutdown chemistry evolutions have shown the iron will be released at insignificantly low levels. Although nickel concentrations as high as 12 ppm may be expected, based on consideration of the counter ions present in the sump fluids and applicable chemistry conditions, it is not considered likely that any insoluble nickel compounds would be generated. This includes consideration of such possible species as phosphates, silicates, borates, and hydroxides/oxyhydroxides.. Based on experience with plant shutdown chemistry, it is considered likely that no more than a small quantity (<5 kg) of oxide (i.e., magnetite, nickel ferrite, etc.) would be released from the internal surfaces of the Reactor Coolant System during a LOCA. Any such material released would be in the form of a dense, crystalline deposit that would not be readily transported, and would not be expected to affect sump screen performance.

Table 4.2-1: Dissolution Test Matrix

	Test Conditions			Measurement	
Run	Material	Solution	T (°F)	Intermediate	Final
1	1. Aluminum sheet	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
2		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
3		pH 8 NaOH	265	ICP	Mass, ICP
4		pH 8 NaOH	190	ICP	Mass, ICP
5		pH 12 NaOH	265	ICP	Mass, ICP
6		pH 12 NaOH	190	ICP	Mass, ICP
7	2. Cal-Sil Insulation	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
8		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
9		pH 8 NaOH	265	ICP	Mass, ICP
10		pH 8 NaOH	190	ICP	Mass, ICP
11		pH 12 NaOH	265	ICP	Mass, ICP
12		pH 12 NaOH	190	ICP	Mass, ICP
13	3. NUKON Fiberglass	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
14		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
15		pH 8 NaOH	265	ICP	Mass, ICP
16		pH 8 NaOH	190	ICP	Mass, ICP
17		pH 12 NaOH	265	ICP	Mass, ICP
18		pH 12 NaOH	190	ICP	Mass, ICP
19	4. Other Fiberglass	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
20		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
21		pH 8 NaOH	265	ICP	Mass, ICP
22		pH 8 NaOH	190	ICP	Mass, ICP
23		pH 12 NaOH	265	ICP	Mass, ICP
24		pH 12 NaOH	190	ICP	Mass, ICP
25	5. Powdered Concrete	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
26		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
27		pH 8 NaOH	265	ICP	Mass, ICP
28		pH 8 NaOH	190	ICP	Mass, ICP
29		pH 12 NaOH	265	ICP	Mass, ICP
30		pH 12 NaOH	190	ICP	Mass, ICP
31	6. Mineral Wool	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
32		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
33		pH 8 NaOH	265	ICP	Mass, ICP
34		pH 8 NaOH	190	ICP	Mass, ICP
35		pH 12 NaOH	265	ICP	Mass, ICP
36		pH 12 NaOH	190	ICP	Mass, ICP
37	7. Microporous Insulation	4400 ppm B (as H_3BO_3)	265	ICP	Mass, ICP
38		4400 ppm B (as H_3BO_3)	190	ICP	Mass, ICP
39		pH 8 NaOH	265	ICP	Mass, ICP
40		pH 8 NaOH	190	ICP	Mass, ICP
41		pH 12 NaOH	265	ICP	Mass, ICP

42		pH 12 NaOH	190	ICP	Mass, ICP
43	8. Fiber Fax	4400 ppm B (as H₃BO₃)	265	ICP	Mass, ICP
44		4400 ppm B (as H₃BO₃)	190	ICP	Mass, ICP
45		pH 8 NaOH	265	ICP	Mass, ICP
46		pH 1 8 NaOH	190	ICP	Mass, ICP
47		pH 12 NaOH	265	ICP	Mass, ICP
48		pH 12 NaOH	190	ICP	Mass, ICP

ICP   = analysis of dissolved elements by ICP

Mass   = Final material mass

4.2.3 Precipitation Testing

The dissolved material from the Materials Dissolution Testing produced at maximum temperatures determined from industry surveys were cooled to 80°F to test for chemical precipitate formation. The value of 80°F is typical of long-term equilibrium pool temperatures, and can be reliably controlled in a laboratory environment.

The pH of the boric acid solutions were adjusted to pH = 8 in separate tests using sodium tetraborate and trisodium phosphate.

The following characteristics of the precipitate were measured using standard techniques:

- •Precipitate mass
- •Precipitate settling rate
- •Settled precipitate volume
- •Precipitate filterability

The potential for interaction between the different containment materials to produce precipitation beyond that produced from a single material were investigated with screening tests that measure the mass of precipitates only. Up to 10 combinations of material dissolution products were made before cooling and pH adjustment. The selection of the combinations were made on the basis of the most likely reactions. The results of the dissolution tests, combined with literature data, guided the selection of solutions to combine.

The precipitation test matrix is shown in the following table. Note: Solution numbers in the Solution A and Solution B columns refer to dissolution test numbers.

Table 4.2-2: Precipitation Test Matrix

PPT Run	Solution A	Solution B	Note
1	1	-	Precipitation from cooling
2	3	-	Precipitation from cooling
3	5	-	Precipitation from cooling
4	7	-	Precipitation from cooling
5	9	-	Precipitation from cooling
6	11	-	Precipitation from cooling
7	13	-	Precipitation from cooling
8	15	-	Precipitation from cooling
9	17	-	Precipitation from cooling
10	19	-	Precipitation from cooling
11	21	-	Precipitation from cooling
12	23	-	Precipitation from cooling
13	25	-	Precipitation from cooling
14	27	-	Precipitation from cooling
15	29	-	Precipitation from cooling
16	31	-	Precipitation from cooling
17	33	-	Precipitation from cooling
18	35	-	Precipitation from cooling
19	37	-	Precipitation from cooling
20	39	-	Precipitation from cooling
21	41	-	Precipitation from cooling
22	43	-	Precipitation from cooling
23	45	-	Precipitation from cooling
24	47	-	Precipitation from cooling
25	1	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
26	7	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
27	13	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
28	19	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
29	25	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
30	31	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
31	37	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
32	43	TSP pH 8	Precipitation of Calcium and Magnesium Phosphates
33	1	Borax pH 8	Precipitation due to pH Increase
34	7	Borax pH 8	Precipitation due to pH Increase
35	13	Borax pH 8	Precipitation due to pH Increase
36	19	Borax pH 8	Precipitation due to pH Increase
37	25	Borax pH 8	Precipitation due to pH Increase
38	31	Borax pH 8	Precipitation due to pH Increase
39	37	Borax pH 8	Precipitation due to pH Increase
40	43	Borax pH 8	Precipitation due to pH Increase
41-50	X	Y	Combinations will be selected on basis of dissolution tests

4.3 TEST OPERATIONS

4.3.1 Test Performer

The organization responsible for performing the bench tests described in this document is the Westinghouse Science and Technology Center (STC). Additional support will be obtained from other qualified facilities, as needed, and will perform under the direction of STC, to support and maintain the schedule identified below.

4.3.2 Procedures

Existing Westinghouse procedures and industry standard practices were used to prepare test specimens, perform testing, and collect the data identified in this document. Actions that are different from Westinghouse or industry standard practices were documented.

4.3.3 Equipment and Instrumentation

The following is a general description of equipment and instrumentation that were used in this test program.

1. A collection of heated reaction vessels, each having a volume of less than 1 gallon, were used for the dissolution testing.

2. Settling experiments were conducted in centrifuge tubes.

3. The filtration was performed with a commercial glass fiber filter. Scanning Electron Microscopy (SEM) techniques were used to examine the collection of filtrate, if determined to be appropriate. This will allow identification of the filtrate material as well as the mode of filtrate collection.

4.3.4 Documentation

Log books were maintained to record the activities associated with the performance of each test.

4.3.5 Photographs

Digital photographs were taken as follows:

Materials Dissolution Testing

1. Test samples, before being placed in solution

Precipitation Generation Testing

1. Precipitate settling rate; an attempt will be made to "mark" and "time phase" the photos to illustrate settling

2. The amount of settled precipitate; to illustrate the volume of precipitate

4.4 REFERENCES

4.4-1   "Test Plan: Characterization of Chemical and Corrosion Effects Potentially Occurring Inside a PWR Containment Following a LOCA," Revision 13, July 20, 2005.

4.4-2   Generic Letter GL 2004-02, "Potential Impact of Debris Blockage on Emergency Recirculation during Design Basis Accidents at Pressurized Water Reactors," September 13, 2005.

4.4-3   STD-MC-05-15, "Test Plan: Measurement of Chemical Effects Design Margin in Containment Sump Screens," Revision 4, November 22, 2005.

5.0 BENCH TESTING

The bench testing experiments explored the dissolution characteristics of containment materials and the characteristics of precipitates that were generated from dissolved containment materials. The experimental design for the dissolution tests and precipitation tests has been described in Section 4.0. The implementation of the test plan and the results that were obtained are described below.

5.1 PARAMETER SELECTION

The test plan stated that the final selection of operating temperatures, pH values, sampling times and materials would be made on the basis of the industry survey considering input from the NRC. These parameters were set as described below.

5.1.1 Dissolution Testing Temperature and pH

The industry survey data was reviewed and it was concluded that the pH levels of 4.1, 8.0 and 12.0 in the test plan adequately spanned the pH range expected in the sump after a LOCA. Likewise, the test plan maximum temperature of 265°F +/- 5°F was determined to be adequate in that it bounded all but one of the maximum temperature values in the industry survey. Because the one outlier was only 10°F higher than the maximum temperature range and lasts for just the first 40 seconds after the Reactor Coolant System (RCS) break, this brief spike in temperature is not expected to have a significant impact on the overall dissolution behavior considered over 90 minutes.

Sampling times for the dissolution test were set at 30 minutes, 60 minutes, and 90 minutes. These rather short dissolution times were selected for a number of reasons. The most important was that pH vs. time plots provided with the surveys indicated that the most extreme pH values were typically maintained for only a few minutes, so long term testing at the extreme values would not represent the expected containment conditions. Short term dissolution rates obtained with the 30, 60, and 90 minute sampling would be expected to bound long term corrosion rates in most cases since most corrosion/dissolution reactions slow with time. This would not be the case for materials with an induction period for dissolution, but the existence of an induction period could be identified by increasing dissolution during the initial 90 minutes. The testing time could then been extended for such a material. Finally, some of the existing dissolution data for CalSil suggested that dissolution rates were quite high, and short sampling times would be required to measure dissolution rates before saturation occurred.[1]

5.1.2 Containment Materials

The materials investigated in the dissolution tests were selected so that at least one member of each of the containment material categories was included. See Section 3.2 for the classification of containment materials by chemical composition. Initially, the list included:

- Aluminum sheet
- Concrete (ground)

- CalSil
- Nukon Fiberglass
- High Density Fiberglass
- Mineral Wool
- Min-K
- FiberFrax Durablanket
- Interam

The NRC recommended the inclusion of galvanized steel and uncoated carbon steel in a review of the test plan during a program review at the Westinghouse Science and Technology Center on December 6, 2005 so these materials were also added to the dissolution test matrix.

- Galvanized steel
- Uncoated carbon steel

Copper alloy surfaces in containment can be significant but copper was not tested because the corrosion resistance of copper is similar to that of carbon steel or galvanized steel[1] and only very low solution copper concentrations were observed in the ICE tests. Previous testing by Oak Ridge National Laboratory has also concluded that "the corrosion rate of copper and the copper alloys is low enough in the alkaline borate solution to be of no practical concern."[2]

Some dissolved material and suspended solids would be released from the reactor coolant system (RCS) during a LOCA. One would expect the levels to be similar to that experienced during a normal PWR shutdown. Dissolved nickel is the main component released from the RCS.[1] Nickel was not included in the materials investigated in the bench testing because the total quantity of nickel expected was small compared to other materials as shown in Figure 5.1-1.

Figure 5.1-1: Nickel Releases during Shutdowns for Three and Four Loop PWRs
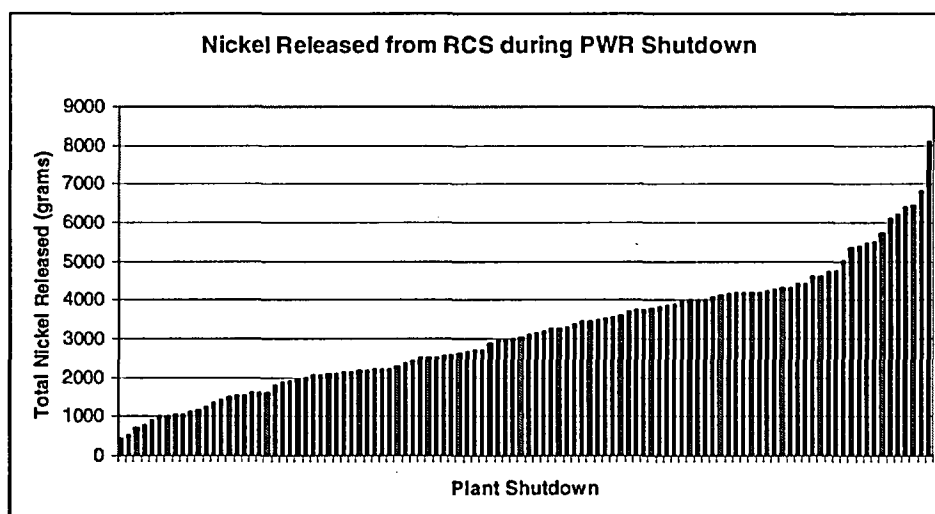
A color macrograph of each of the tested materials is given in Figure 5.1-2. The approximate proportions of the materials used are shown except for carbon steel, where two and one-half coupons were tested. A more detailed description of materials is given in the remainder of the section.
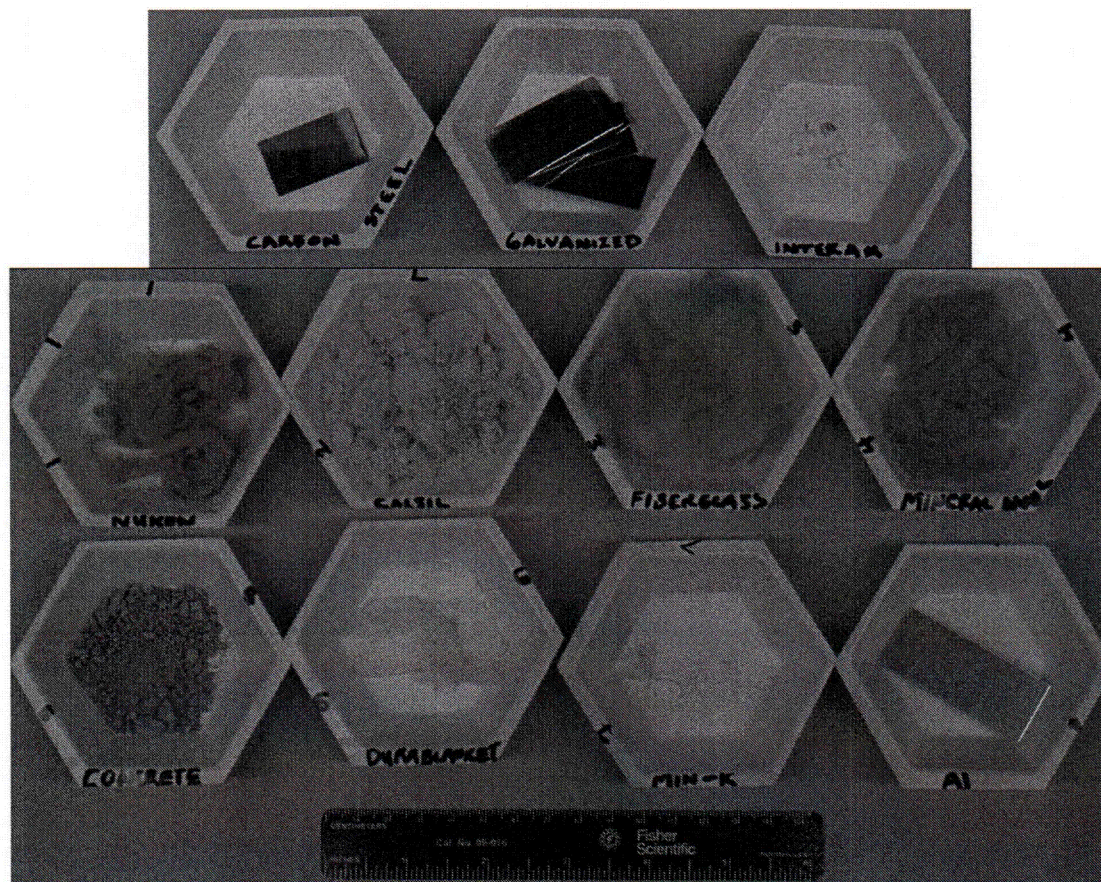
Figure 5.1-2: Light Macrophotos Starting Materials

5.1.2.1 Containment Material Details

Although carbon was detected in a number of the SEM samples, the majority of the carbon is most likely an artifact of the sample preparation. For insulation materials in which carbon may be present as an organic binder, the presence of carbon could reduce the measured dissolution rates, but experimentally, no effect was observed.

<u>Aluminum Sheet</u>

Aluminum Alloy 1100 (Commercially Pure) sheet 0.032 inches thick was supplied by McMaster Carr (Part Number 88685K11). The sheeting was cut with a shear into coupons that were 20 mm wide and either 31, 42 or 61mm long. The coupons were cleaned in water and ethanol but were not polished. The coupons were reflective, suggesting that the native oxide was relatively thin.

An SEM/EDS analysis was performed on the coupon surface. The SEM image is shown in Figure 5.1-3. Only the elements aluminum and iron were detected on the surface. Concentrations are given in Table 5.1-2.
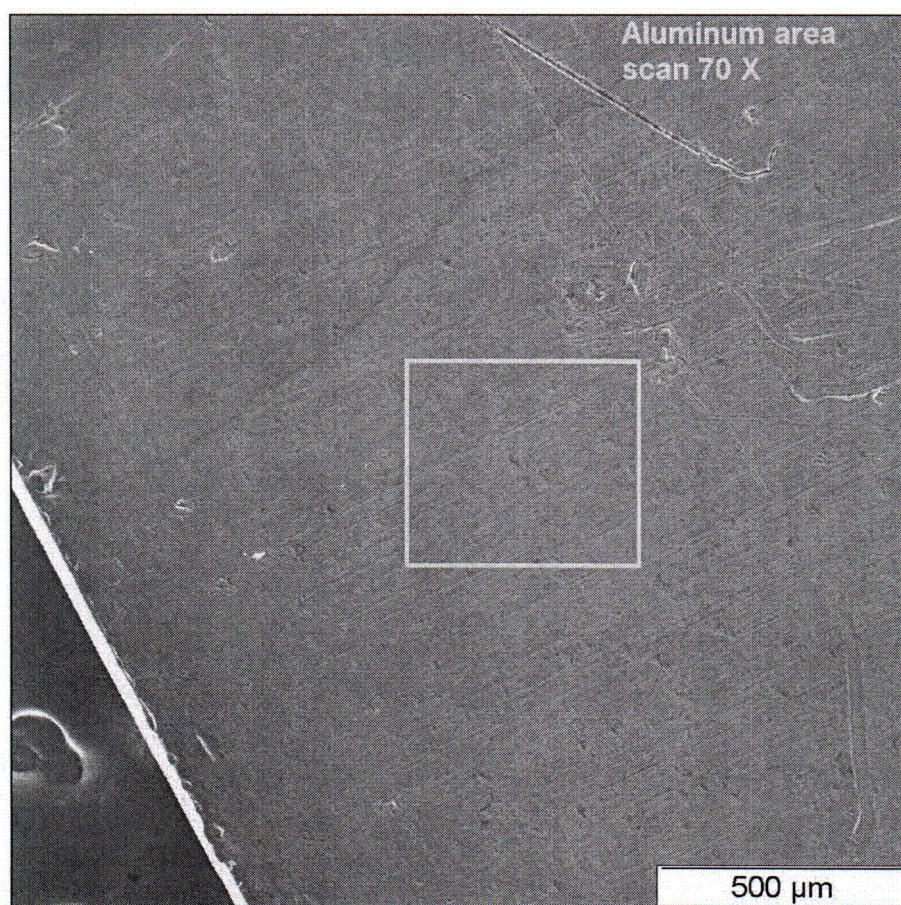
Figure 5.1-3: SEM Image of an Aluminum Coupon Surface

Concrete

Concrete was supplied by Performance Contracting, Inc. (PCI). The concrete had been crushed by PCI, and a large range of particle sizes were present. The largest were near 10 mm in diameter, while the smallest were only a few microns in diameter. The surface area of concrete exposed to solution will control the dissolution rate, so the surface areas of several concrete samples were measured by the BET method. The results are shown in Table 5.1-1.

Table 5.1-1: Concrete Specific Surface Area by BET

Sample Number	Specific Surface Area (m^2/g)
1	9.78
2	8.49
3	9.84
4	9.39
5	9.58
6	8.34
Average	9.24

The elemental composition determined by SEM/EDS is given in Table 5.1-2. Calcium, silicon, and oxygen were the primary components of the concrete. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of two concrete particles is shown in Figure 5.1-4.

500 µm
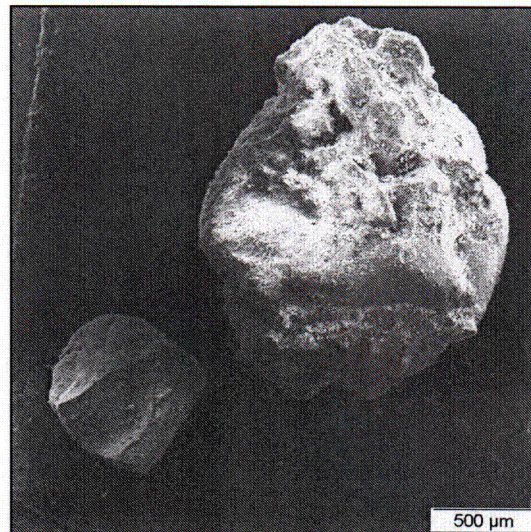
Figure 5.1-4: SEM Image of Two Concrete Particles

CalSil

CalSil was supplied by PCI, Inc. The CalSil had been crushed into a powdered form which is standard for GSI-191 testing.

The elemental composition determined by SEM/EDS is given in Table 5.1-2. Calcium, silicon, and oxygen were the primary components of the concrete. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging. The composition was quite similar to that of concrete.

An SEM image of CalSil particles and fibers is shown in Figure 5.1-5. The clumps of calcium silicate particles were loosely bound together with organic fibers.

500 µm

Figure 5.1-5: SEM Image of CalSil Fibers and Particles

Nukon Fiberglass

Nukon fiberglass was supplied by PCI, Inc. in a baked and shredded form.

The elemental composition of the Nukon as determined by SEM/EDS is given in Table 5.1-2. An area scan of a mass of fibers revealed that sodium, calcium, silicon, aluminum and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of Nukon fiberglass fibers is shown in Figure 5.1-6.

500 µm
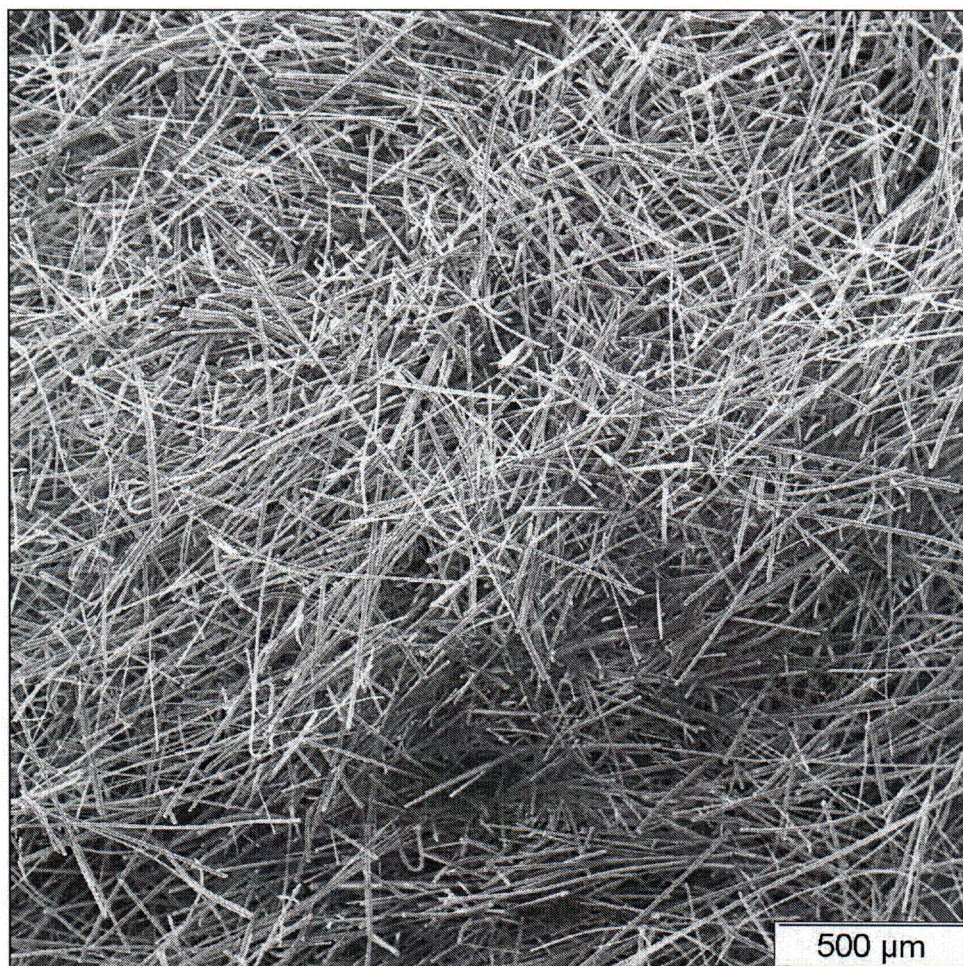
Figure 5.1-6: SEM Image of Nukon Fibers

High Density Fiberglass

The high density fiberglass was supplied in unbaked, shredded form by PCI. Since the high density fiberglass was unbaked, the organic binders present during testing could produce a non-conservative lower dissolution rate. However, this behavior was not observed as evidenced by the larger mass release in Table 5.2-2 for the high density fiberglass than that for the baked Nukon fiberglass.

The elemental composition of the high density fiberglass was determined by SEM/EDS and is given in Table 5.1-2. An area scan of a mass of fibers revealed that sodium, calcium, silicon, aluminum and oxygen were the primary components. Sulfur was a minor component not found in the Nukon sample. Carbon was detected at higher levels than in the Nukon fiberglass sample. The source of the additional carbon was likely the organic binder. The ratios of the main elemental components were similar between Nukon fiberglass and high density fiberglass. This is evident in Table 5.1-3, where oxygen and carbon have been removed from the analyses and the remaining elemental concentrations were renormalized.

An SEM image of high density fiberglass fibers is shown in Figure 5.1-7. Binding material can be seen connecting the fibers.

500 µm
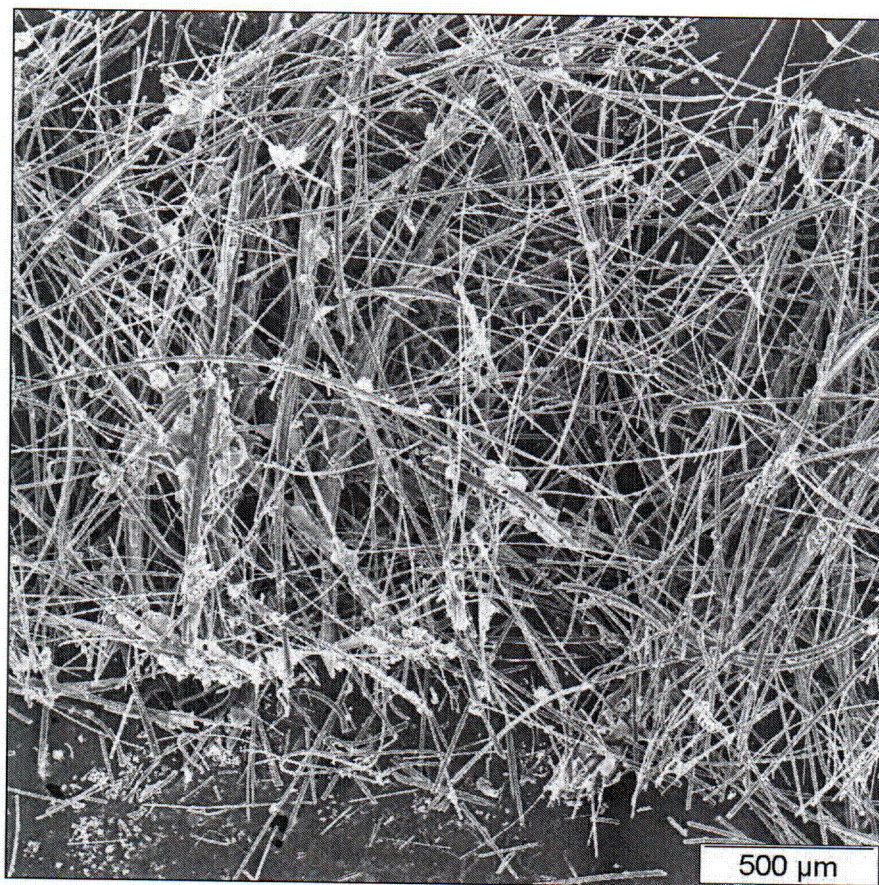
Figure 5.1-7: SEM Image of High Density Fiberglass Fibers

Mineral Wool

Mineral wool was supplied in shredded form by PCI, Inc. The mineral wool was not baked. Although this material was not baked, there was no clear evidence of organic binders.

The elemental composition of the mineral wool was determined by SEM/EDS and is given in Table 5.1-2. An area scan of a mass of fibers revealed that magnesium, calcium, silicon, aluminum, iron and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of the mineral wool sample is shown in Figure 5.1-8. The fibers and glassy droplets shown in the figure all had about the same chemical composition.

500 µm
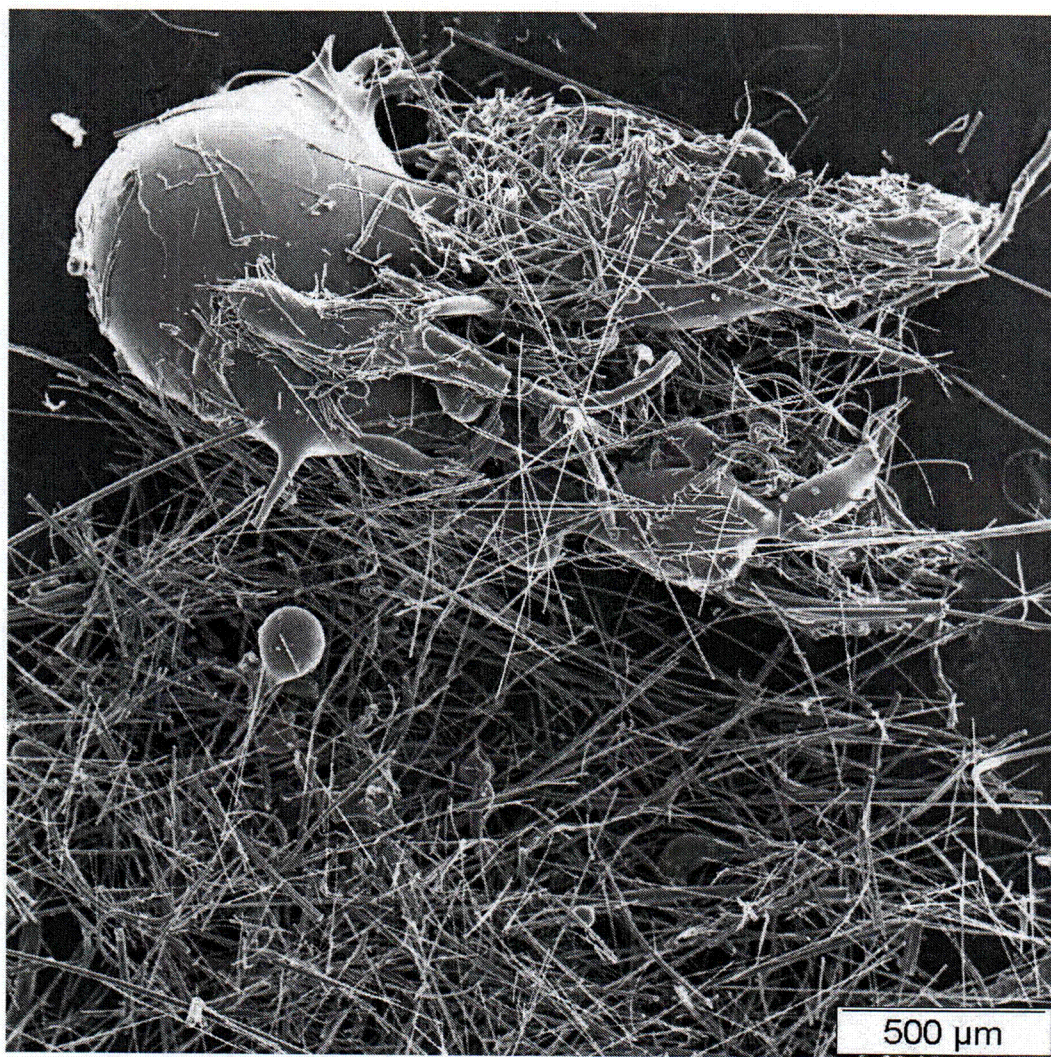
Figure 5.1-8: SEM Image of Mineral Wool

MIN-K

MIN-K was supplied in shredded form by PCI, Inc. The MIN-K was not baked. The presence or absence of binding materials was not clear, but as discussed for the high density fiberglass, the presence of organic binders may not exert a strong influence on dissolution behavior.

The elemental composition of the MIN-K was determined by SEM/EDS and is given in Table 5.1-2. It should be noted that the MIN-K was not homogeneous. E-Glass fibers were found to be located both in piles and in a woven fabric. Silica and titania particles clung to the fibers, and were present in separate clumps. An area scan in a region that contained both fibers and particles revealed that silicon, oxygen, titanium, and calcium were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging. Boron was a likely component of the fibers but it could not be quantified with the EDS system that was used.

An SEM image of the MIN-K sample is shown in Figure 5.1-9.
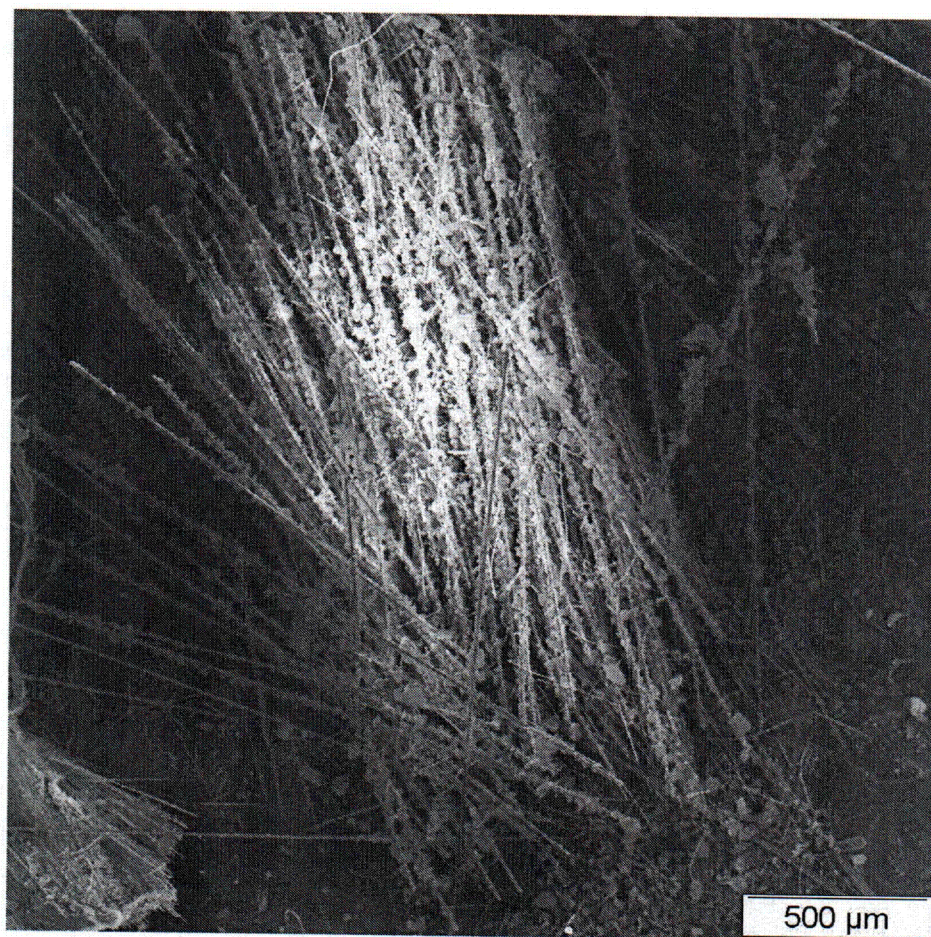
Figure 5.1-9: SEM Image of Fibers and Attached Particles in the MIN-K Sample

FiberFrax DuraBlanket

The FiberFrax DuraBlanket was supplied in shredded form by PCI, Inc. The FiberFrax was not baked and did not appear to contain any binders.

The elemental composition of the Fiber Frax was determined by SEM/EDS and is given in Table 5.1-2. The composition was uniform from location to location. The elements silicon, aluminum and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of the FiberFrax Durablank sample is shown in Figure 5.1-10.
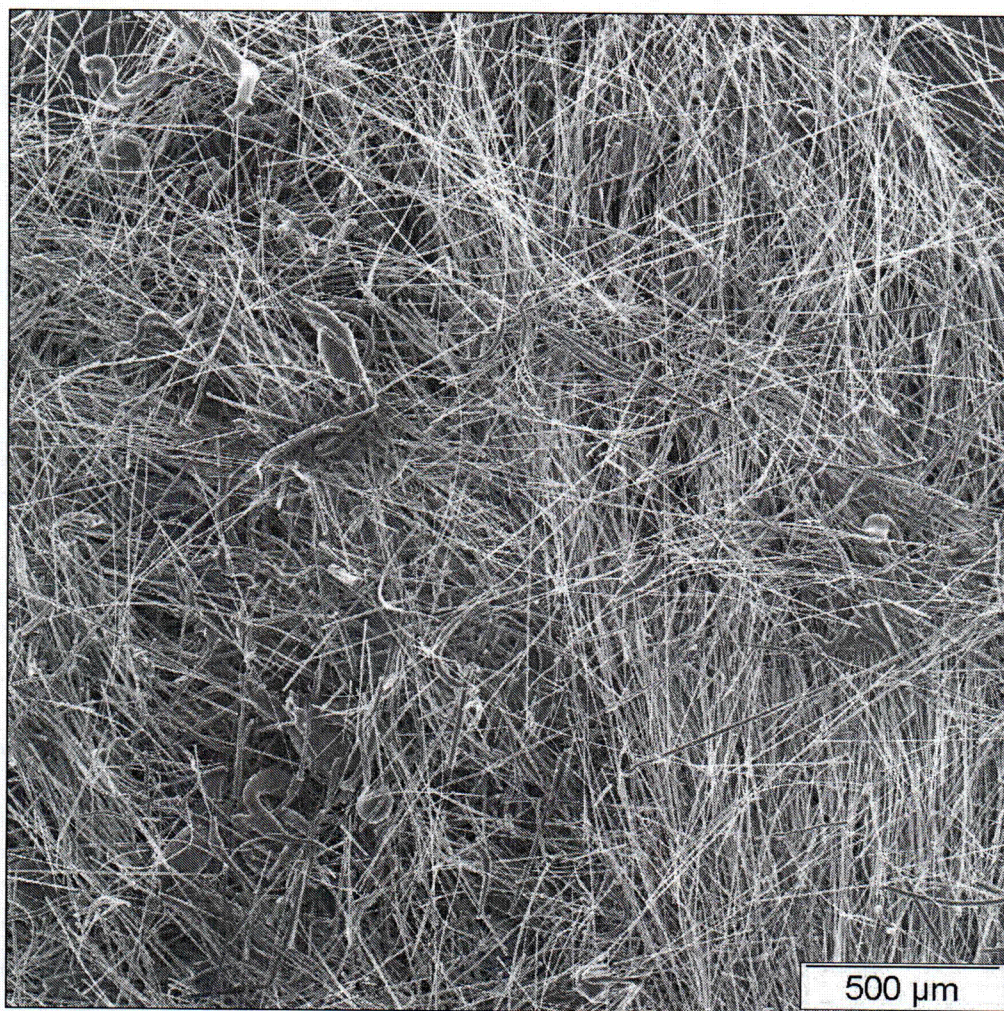
Figure 5.1-10: SEM Image of FiberFrax Durablanket

Interam

The Interam was supplied by Southern Nuclear. The Interam was supplied as a single foil-backed sheet of insulation. The sheet was sampled by slicing a thin strip of material from the edge of the sheet. The samples included the aluminum backing.

The elemental composition of the Interam filler was determined by SEM/EDS and is given in Table 5.1-2. The elements silicon, aluminum, calcium and oxygen were the primary components. Carbon was detected but at least a portion of the carbon signal was due to a carbon coating applied to the sample to improve imaging.

An SEM image of a portion of the Interam sample is shown in Figure 5.1-11.

500 µm
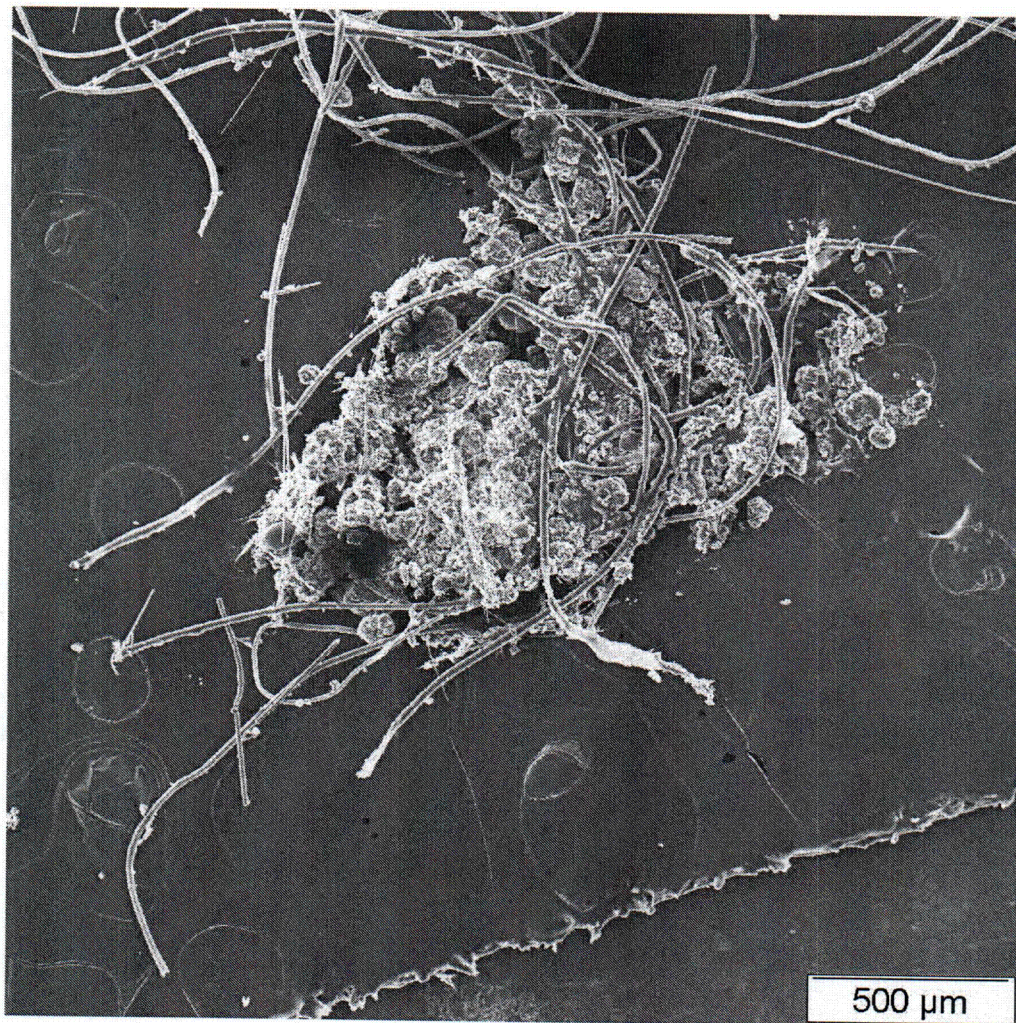
Figure 5.1-11: SEM Image of 3M Interam

Low Alloy Steel

A508 Low Alloy Steel was machined from a weld mock-up used to qualify repair actions. The samples were sectioned from a large piece of material, producing coupons 1.98 x 0.5 x 3.25 cm. The coupons were then cleaned with water and ethanol, but were not polished. The coupons were reflective. Two and one-half coupons were used in each test.

An SEM/EDS analysis a coupon surface was performed. The SEM image is shown in Figure 5.1-12. The detected elements are given in Table 5.1-2.
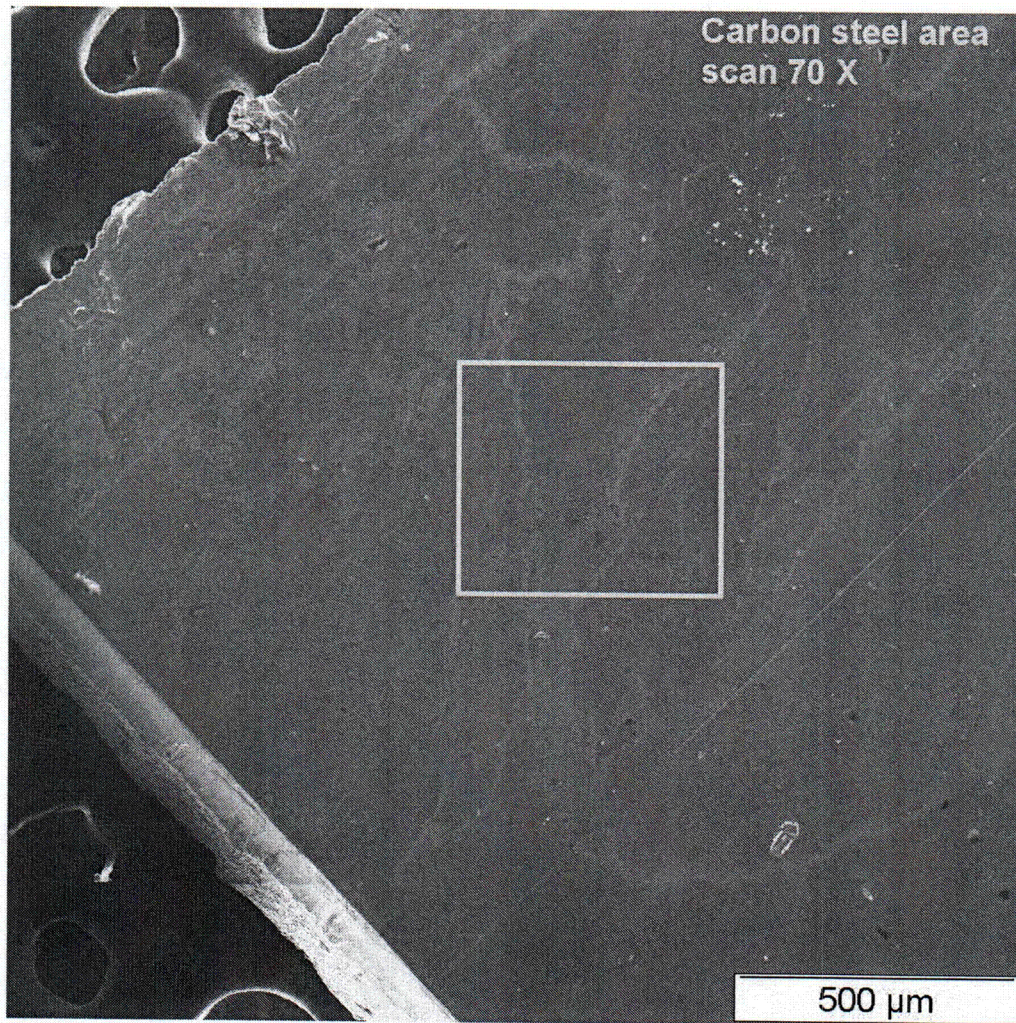
Figure 5.1-12: SEM Image of a Carbon Steel Coupon Surface

Galvanized Steel

Galvanized low carbon steel sheet 0.032 inches thick was supplied by McMaster Carr (Part Number 8943K12). The sheeting was cut with a shear into coupons that were 2.0 cm wide and 3.8 cm long. Six specimens were used in each test. The coupons were cleaned with water and ethanol, but were not polished. The coupons were reflective, suggesting that the native oxide was relatively thin.

An SEM/EDS analysis was performed on a coupon surface. The SEM image is shown in Figure 5.1-13. Only the elements aluminum, oxygen, zinc and iron were detected on the surface. Concentrations are given in Table 5.1-2.
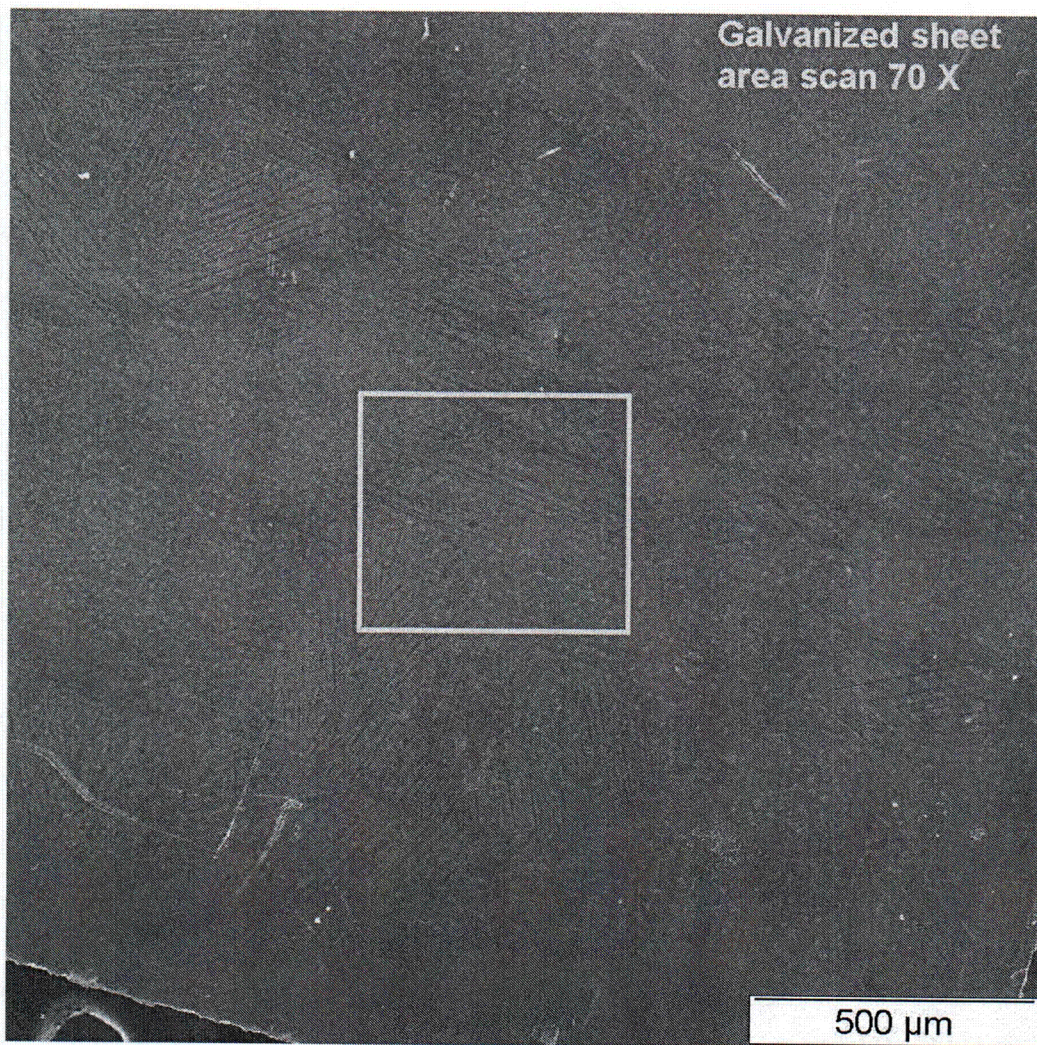

Figure 5.1-13: SEM Image of a Galvanized Steel Coupon Surface

Table 5.1-2: Elemental Composition of Tested Materials by SEM/EDS, Area Scans (Wt%)

Material	Weight Percent														
	C	O	Mg	Al	Si	S	K	Ca	Fe	Na	Mn	Ti	Cr	Ni	Zn
Aluminum				99.57					0.43						
Concrete	30.46	46.59	0.65	2.45	6.74	0.58	0.29	11.87	0.36						
CalSil	27.99	41.31	0.29	2.24	11.50		0.46	14.08	0.87	1.25					
Nukon	26.65	46.26	0.82	1.43	14.39		0.33	2.95	0.15	6.98	0.03				
High Density Fiberglass	59.03	31.17	0.26	0.42	5.09	0.29	0.14	1.07	0.13	2.41					
Mineral Wool	34.80	38.13	3.21	3.49	8.90		0.14	8.81	1.92	0.36	0.08	0.15			
MIN-K	38.33	51.08		0.81	7.48			1.49				0.81			
Fiber Fax Durablanket	33.05	45.78		11.27	9.91										
Interam	40.65	49.01		8.67	1.46			0.21							
Carbon Steel				1.53	0.35	0.80			95.51		0.89		0.43	0.50	0.50
Galvanized Steel		6.29		3.20					1.62						88.98

Table 5.1-3 Normalized Elemental Composition- Carbon and Oxygen Removed (Wt%)

Material	Normalized Weight Percent												
	Mg	Al	Si	S	K	Ca	Fe	Na	Mn	Ti	Cr	Ni	Zn
Aluminum		99.6					0.4						
Concrete	2.8	10.7	29.4	2.5	1.3	51.7	1.6						
CalSil	0.9	7.3	37.5		1.5	45.9	2.8	4.1					
Nukon	3.0	5.3	53.1		1.2	10.9	0.6	25.8	0.1				
High Density Fiberglass	2.7	4.3	51.9	3.0	1.4	10.9	1.3	24.6					
Mineral Wool	11.9	12.9	32.9		0.5	32.6	7.1	1.3	0.3	0.6			
MIN-K		7.6	70.6			14.1				7.6			
Fiber Fax Durablanket		53.2	46.8										
Interam		83.8	14.1			2.0							
Carbon Steel		1.5	0.3	0.8			95.0		0.9		0.4	0.5	0.5
Galvanized Steel		3.4					1.7						94.9

5.1.2.2 Material Amounts Added

The material additions were scaled to the chemical reactor volume. Table 5.1-4 below presents the amount of material added for a 100 ml chemical reactor volume. The amounts were scaled to maintain a given material-to-coolant volume ratio, specified in terms of surface area of material to coolant volume or material volume to coolant volume. The target ratios were the maximum ratios from Table 3.1-1 reported in the industry survey. For the dissolution experiments, the material was measured by mass for fibrous materials as a matter of convenience, with material densities being used to convert between volume and mass. The material densities with the exception of concrete are obtained from Table 3-2 of Reference 5.1-5.

Table 5.1-4: Target Material Additions

Material	Material/Coolant Ratio Value	Units	Assumed Density (lb/ft^2)	Target Addition for 100 ml solution Mass (g)	Surface Area (cm^2)
Fiberglass Insulation Max Ratio	0.14	ft3/ft3	4	0.900	
Cal Sil Insulation Max Ratio	0.18	ft3/ft3	14.5	4.180	
Min-K Max Ratio	0.001	ft3/ft3	16	0.026	
Mineral Wool Max Ratio	0.04	ft3/ft3	10	0.640	
DuraBlanket	0.0213	ft3/ft3	12	0.410	
Interam Only Ratio	0.00027939	ft3/ft3	60	0.027	
▓▓▓▓▓▓	▓▓▓▓	▓▓▓	▓▓▓	▓▓▓	▓▓▓
Aluminum Max Ratio	5.42	ft^2/ft^3			17.8
Carbon Steel Max Ratio	10.78	ft^2/ft^3			35.4
Zinc Max Ratio	27.98	ft^2/ft^3			91.8

The concrete addition was not scaled to any value derived from the industry survey because exposed concrete in containment is typically expressed in surface area, and the surface area of the crushed concrete that was supplied was not known when the tests were begun. A value of 4.0 g/100 ml was chosen arbitrarily. Later measurements of the concrete surface area indicated that only 0.0002 g of the powder was needed to maintain the desired material to coolant ratio of 4.79 ft^2/ft^3. The concentrations of calcium due to dissolution of concrete obtained in the dissolution tests were much higher than would be actually observed and, in this sense, the amount of concrete used was highly conservative. However, the degree of conservatism in the model calculations is not directly related to the concrete to coolant ratio, and the amount of concrete used was suitable for use in model development.

5.1.3 References

5.1-1   J. Oras, J. H. Park, K. Kasza, K. Natesan, and W. J. Shack, "Chemical Effects/Head-Loss Testing Quick Look Report, Tests 1&2, September 16, 2005, NRC IN 2005-26 PT2.

5.1-2   V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

5.1-3   J. C. Griess and A. L. Bacarella, "Design Considerations of Reactor Containment Spray Systems-Part III. "The Corrosion of Materials in Spray Solutions", Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.

5.1-4   PWR Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. TR-105714-V2R5.

5.1-5   NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

5.2   DISSOLUTION AND PRECIPITATION TESTS

The testing described in this section was meant to develop information to supplement and augment the information obtained from the PWR Industry "Integrated Chemical Effects Test" (ICET) program that looked at chemical reactions that can occur in PWR containments after a loss of coolant accident. In five (5) tests, the ICET program examined the long-term chemical reactions and the associated chemical reaction products that may occur in a simulated containment sump environment. The ICET program tests were performed using two (2) types of thermal insulation materials and three (3) pH buffer agents.

The dissolution and precipitation tests performed during this program were done at a smaller "bench level" scale. The primary objective of the current program was to examine more insulation materials in different pH boric acid solutions over a wider range in temperature, focusing on high temperatures that may be present at the early stages of a LOCA. The testing examined dissolution of insulation materials and potential precipitate reactions that may affect performance of containment sump screens. This simplified "bench level" plan allowed a large number of tests to be completed in a time and cost effective manner.

5.2.1   Functional Requirements

The functional requirements listed below were used to guide the design and construction of the dissolution apparatus and the equipment used for precipitation characterization.

The chemical reaction apparatus must be able to measure:

1. The dissolution rates of various containment materials when contacted with simulated solutions

2. The characteristics of precipitates that form in the coolant solutions after dissolution of containment materials followed by changes in temperature and/or chemistry. The characteristics to be measured are:

    *   Precipitate Mass

    *   Precipitate Settling Rate

- Precipitate Volume
- Precipitate Filtering Characteristics

These high level functional requirements translate into the following equipment requirements:

Reaction Vessel

1. Must be chemically inert over the temperature range of 70°F to 270°F.

2. Must be able to withstand pressures up to 21 psig at 270°F. (Note: This is necessary so that the solution design temperature can be held at the maximum temperature without boiling away. The vapor pressure of water at 270°F is 35.4 psia. Thus, the differential pressure across the reactor will be 35.4-14.7 psia = 20.7 psig)

3. Must have means for introduction of sample coupons and removal after the test.

4. The temperature equilibrium within the vessel must occur (± 5°F) within 10 minutes of test initiation (contact between the solution and containment material). This is required because short term dissolution rates are being measured. Samples will be taken at 15 to 30 minute intervals.

5. Must have a means for mixing/stirring

Heating System

1. Must be capable of achieving a maximum temperature of at least 270°F.

2. Must be capable of controlling temperature within a band of ±5°F.

Cooling System

1. Must be capable of achieving a minimum temperature of at least 70°F.

2. Must be capable of controlling temperature within a band of ±5°F.

Fluid Transfer System

The fluid transfer system must:

1. Transfer fluid to and from the reaction vessel.

2. Be chemically inert over the temperature range of 70°F to 270°F.

3. Withstand pressures up to 21 psig at 270°F.

4. Not release pump wear particles.

5. Provide a means for withdrawing solution samples.

   o Solution withdraw must not remove particulate containment materials being tested.

   o Solution samples must be at least 2.5 ml for ICP analysis with 5.0 ml preferred.

      o   Samples must not be allowed to cool below 90°F during sampling.

      o   The entire sample solution volume must be removed at the end of the test to stop the reaction.

6. Keep temperature above 90°F until discharge into sample vessel or settling cone.

7. Transfer samples at a rate such that the sampling time is short relative to the test time (5 ml within 2 minutes).

8. Minimize cross contamination between samples.

      o   Tubing runs should be as short as possible.

      o   Tubing should be clear to detect deposit formation within the lines.

      o   A means for flushing the tubing between samples should be provided.

Sample Bottles

1. Minimum volume - 5 ml (to allow for one analysis and a repeat)

2. Will not react with the stored solution

3. Must withstand an initial temperature of at least 90°F.

4. Must have a closure that prevents evaporation.

Settling Cone

1. Must withstand a temperature of 90°F.

2. Must have a conical base to increase sensitivity.

3. Must be transparent.

4. Must have a cap to prevent evaporation during settling.

5. Must have a diameter greater than the largest particles expected.

6. Must have graduations so that both the volume of solution and the volume of precipitate can be measured.

Filtration System

1. Must have a means for measuring the pressure across the filter with a resolution of 0.1 psi or better.

2. Must be able to quantitatively transfer the precipitated material to a filter membrane or membranes that can be weighed to determine mass gain.

3. The membrane should remove a particle size fraction similar to that removed by a fibrous bed on a sump screen.

4. The flow rate across the screen should be variable so that the particles can be characterized by their pressure drop verses flowrate curve.

5. The filtration system must withstand the test solutions at a temperature of 90°F without degradation (especially the release of particulates).

5.2.2 Dissolution Tests

Dissolution testing was performed using a series of reaction vessels and solution reservoirs housed in a mid-sized air furnace. The test matrix listing the dissolution tests performed is given in Table 4.2-1. A schematic of the equipments used is shown in Figure 5.2-1 and several photographs showing various features of the equipments are shown in Figures 5.2-2 through 5.2-5.

5.2.2.1 Test Preparation

All test solutions were prepared using reagent grade chemicals including boric acid and sodium hydroxide mixed in deionized water having a starting conductivity < 1 uS/cm. The PWR containment materials tested include: aluminum, FiberFrax, Cal-Sil, carbon steel, concrete, Nukon, other fiberglass, Min-K, Interam, Min-Wool, and zinc.

These materials were either purchased from an appropriate vendor or supplied directly by sponsor utility members. For each material tested, the coupon size was scaled to the volume or surface area for that material in containment using US plant survey data. The coupons were cut to have that appropriate volume or surface area.

Coupons were weighed and measured to determine the starting mass and surface area or volume. All metallic coupons were cleaned and dried.

The first step in the actual testing was to fill the solution reservoirs with the appropriate pH boric acid solution and place that reservoir into the furnace. The solution reservoirs were equipped with pressure relief valves to allow elevated temperature testing under safe operating conditions. The pressure relief valves were set to release if the pressure in the reservoir exceeded the saturation pressure of the test solution at the target test temperature by a minimum of 10 psi. The solution in the reservoir was then heated.
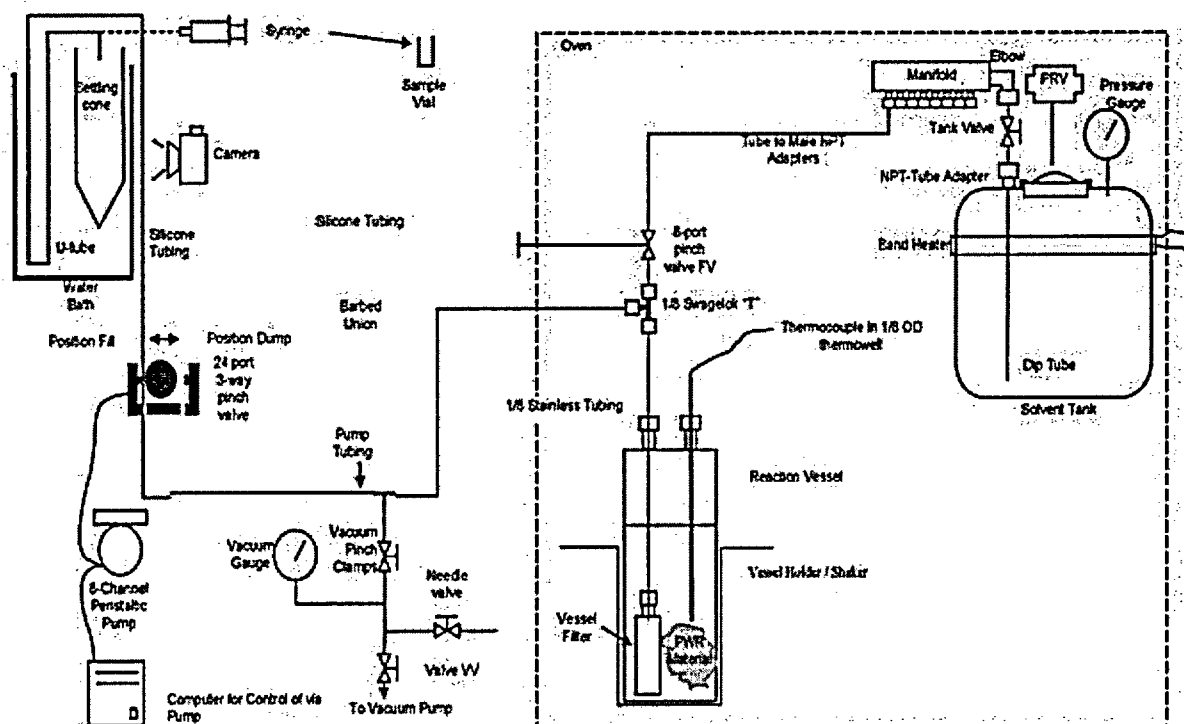
Figure 5.2-1: Bench Tests Equipment Schematic

The solution reservoirs were placed in the oven shown in Figure 5.2-2 and heated. Figure 5.2-3 shows two reservoirs in the back of the furnace. The test solution was distributed by a manifold and directed to one of eight reaction vessels in the furnace that contained the materials to be tested. The reaction vessels are shown in Figures 5.2-4 and 5.2-5. For initial testing at 190°F, Teflon reaction vessels were used. Problems with reliability, especially for testing conducted at 265°F, necessitated switching to stainless steel reaction vessels. In either case, each reaction vessel was equipped with an inlet/outlet tube and a thermowell containing a calibrated thermocouple.

Figure 5.2-2: Oven used to contain the solution reservoirs and reaction chambers
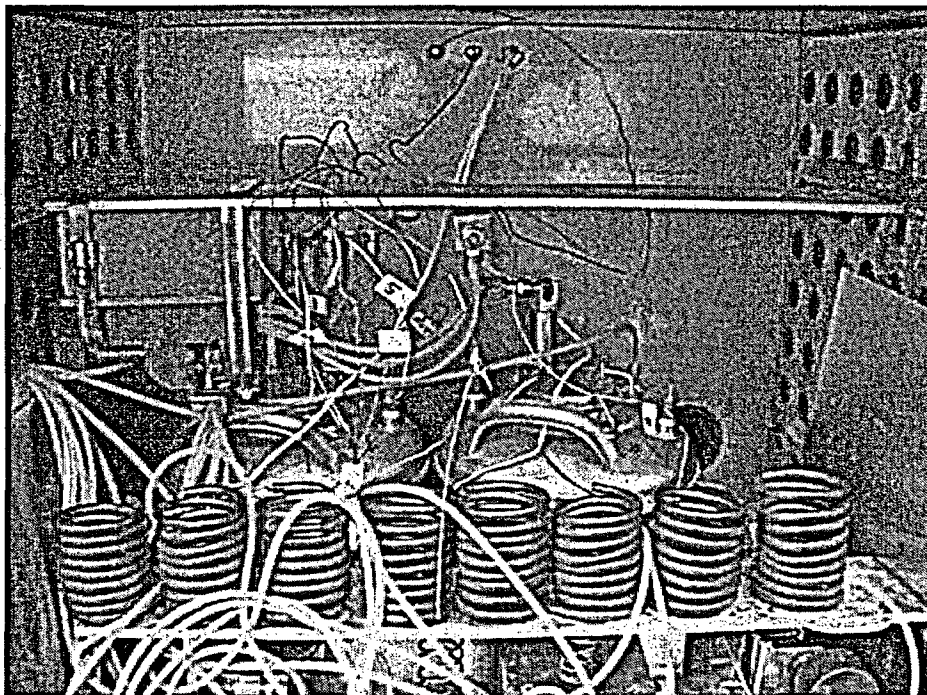
Figure 5.2-3: Photo showing two solution reservoirs inside the high temperature oven. The reaction chambers were installed in the copper coils in the foreground.
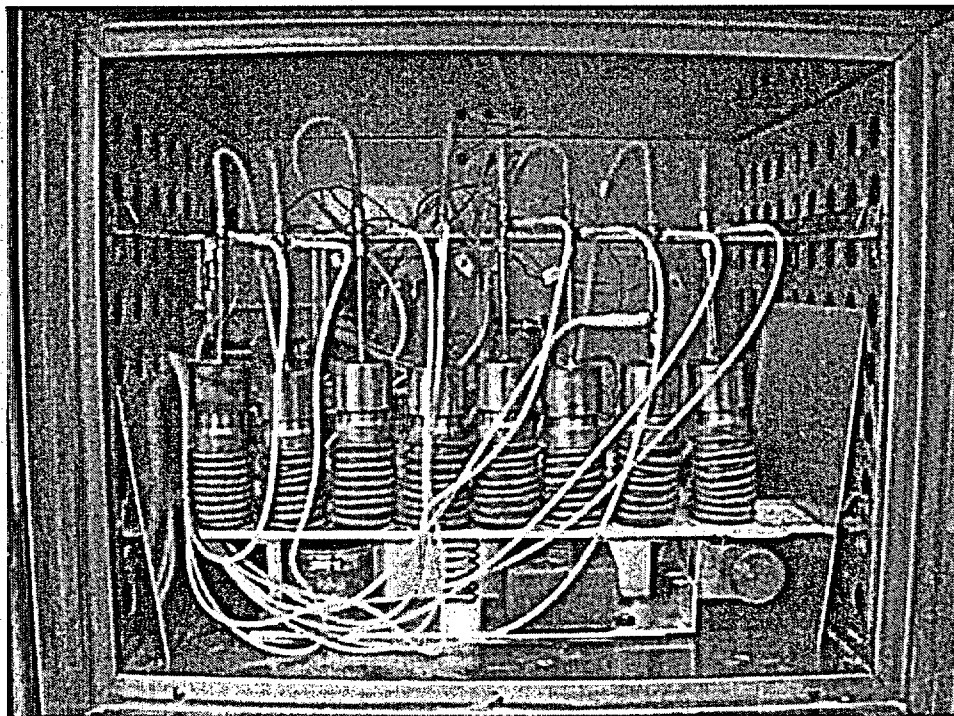
Figure 5.2-4: Eight SS reaction chambers within the oven located on a rocking platform.
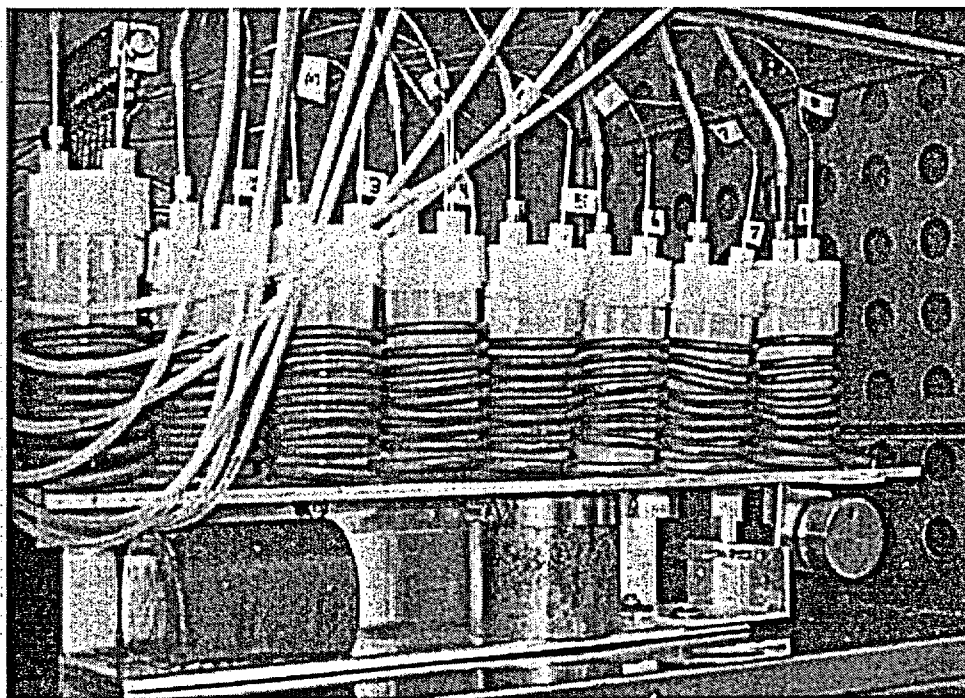
Figure 5.2-5: Teflon reaction vessels were used for many of the experiments at 190°F. Problems with reliability at higher temperatures led to switching to stainless steels vessels.

One test material was placed in each reaction vessel. Typical quantities are shown in Figure 5.2-6. A fresh filter was placed in the reaction chamber to prevent removal of the test materials during solution transfer. The reaction vessels were sealed in place and pressure tested to 60 psig. The appropriate lines were connected and each reaction vessel was placed on a shaker mechanism.

The oven was then heated to temperature. A band heater attached to the solution reservoir allowed the solution to reach test conditions more rapidly. As the oven was heated, temperatures were measured including:

- Furnace temperature

- Temperature of the solution reservoir

- Temperature in each reaction vessel

All thermocouples readings were recorded using a data acquisition system using reading intervals from 3 to 10 seconds.

Pressures were also measured in the solution reservoir and the lines with a combination of pressure gauges and pressure transducers as shown in Figure 5.2-7. The test chambers were initially evacuated and when the test solution reached the target test temperature, the experiments were initiated.
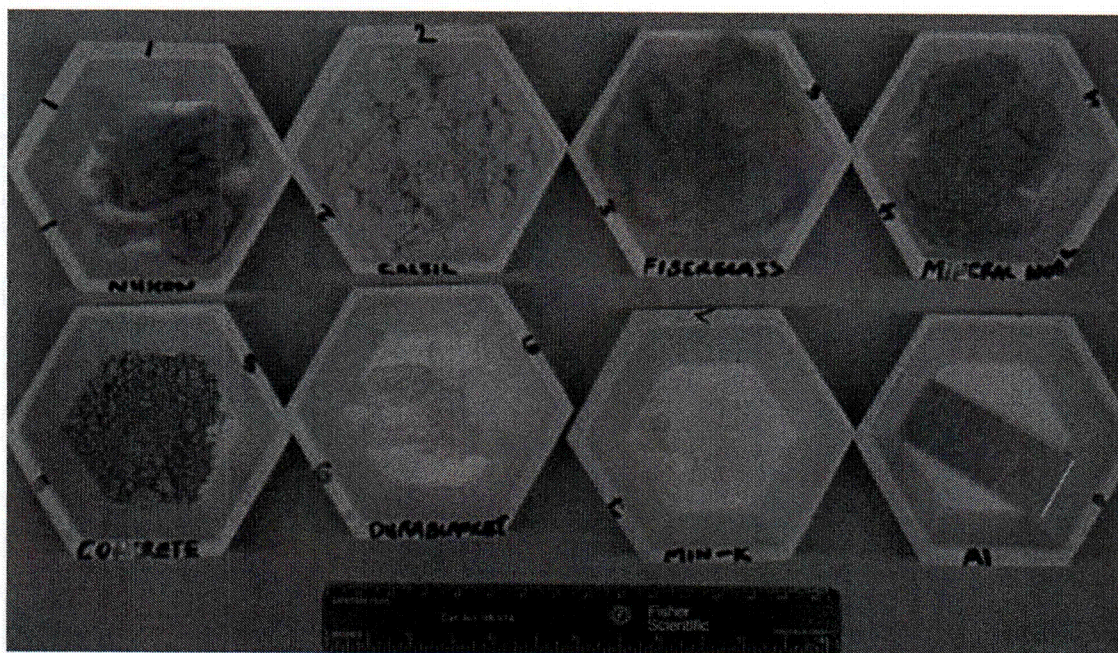
Figure 5.2-6: Representative Tested Material Amounts
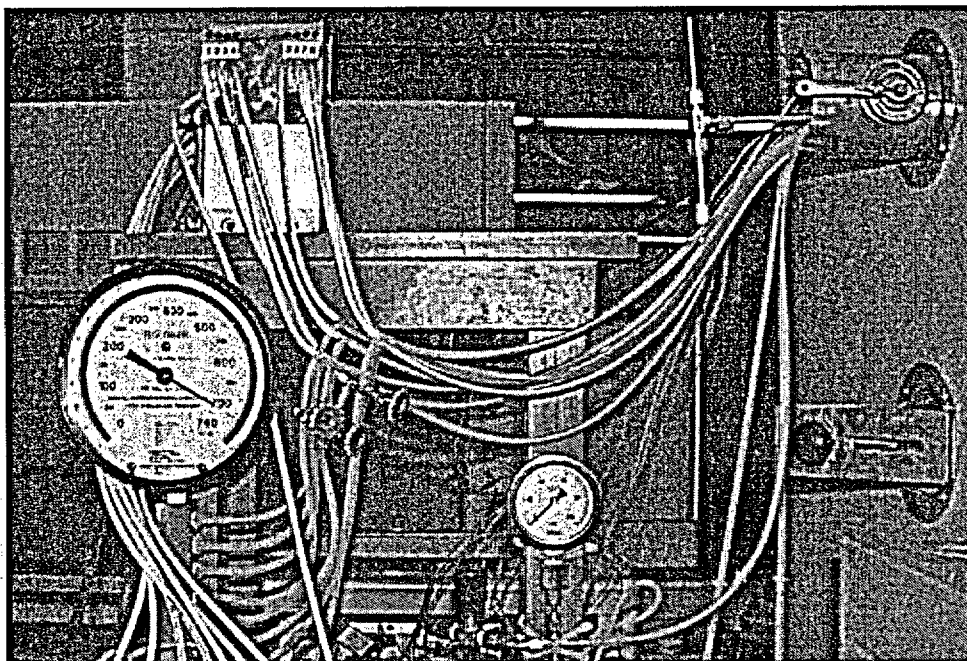
Figure 5.2-7: Pressure gauges and computer operated pinch valve used to control flow and monitor test conditions.

5.2.2.2   Test Procedure

Solution temperatures, pressures and flow rates were measured using the equipment shown in Figure 5.2-8 and Figure 5.2-9. When the temperatures of the solution reservoir and reactors were within acceptable ranges, the 8 port pinch valve to fill the reactor vessels was opened and the computer program used to time the sampling operation was started. At appropriate times, the computer program initiated a flush operation on all lines between the reaction vessel and the water bath containing the settling cones. The flush volume was at least equal to the internal line volume. The boric acid flush solutions flowed into syringes for measurement and disposal. Once an appropriate amount of solution was flushed, the lines were connected to a second series of syringes with plunger stops set to 5 ml. The computer program then opened a 24 port valve to fill syringes. When the syringes were filled, the 24 port valve was closed, and the syringe solutions transferred to pre-labeled sample vials. The samples were sent to Industrial Analytical, Inc. for chemical analysis using ICP-MS, Inductively Coupled Plasma Mass Spectrometry, to determine how much of the PWR test material dissolved into the boric acid solution at that point in time.

At the next sampling time, the process was repeated. Sampling was performed at 0.5, 1 and 1.5 hours. One additional sampling time was sometimes used.
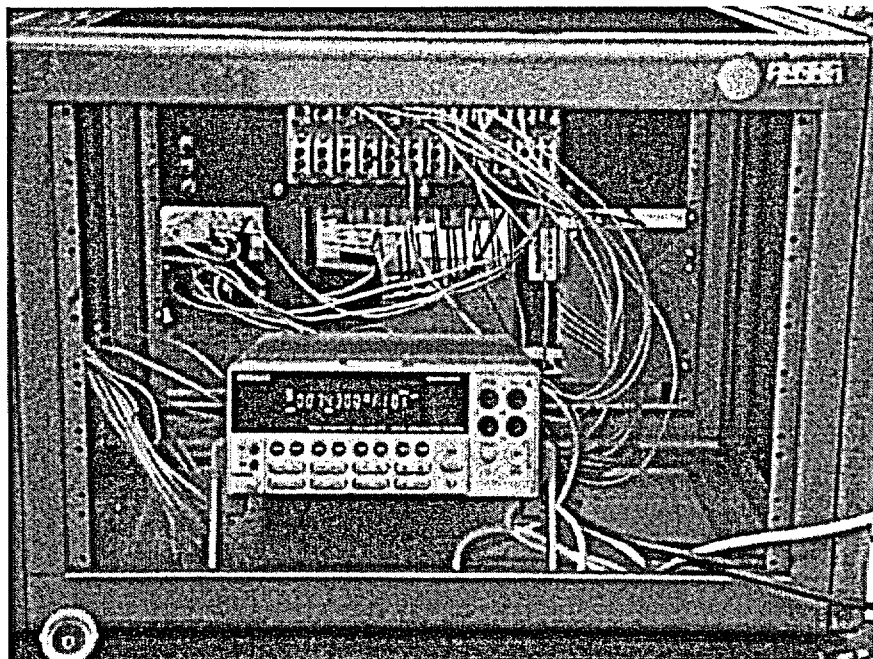
Figure 5.2-8: PC controlled voltmeter used to measure temperature, pressure and flow rates.

Figure 5.2-9: Data acquisition system used to record test parameters and control valves and pump during the dissolution and precipitation phases of the experiment.

5.2.3 Results of Dissolution Tests

The tests were performed as described in the test matrix in Table 4.2-1. Nineteen runs using the dissolution apparatus were made (Runs A through S). With multiple materials being tested in most of the runs, a total of 140 material dissolution tests were performed along with two blank runs. Of the 140 dissolution tests, 52 were rejected because of failure to maintain temperature within the target range or fluid control failures. Concentrations of dissolved chemical species, release rates, and sample mass measurements are given in Appendix A. Of the 88 good runs, only 66 were needed to satisfy the design matrix and these are referred to as "design matrix tests" in the discussion. The other 22 runs were considered replicates. The replicate runs were included in model development to aid in error estimation and to improve the confidence interval for model predictions.

The ICP analyses included analyses for Al, Ca, Si, Mg, P, S, Fe, Zn, and Ti. The values obtained for P, Mg, and Ti were negligible and can be ignored in any chemical effects head loss testing.

The total mass of each element release in the design matrix dissolution tests was calculated by summing the releases for all times, temperatures, and pH levels. The releases included all of the materials tested. The results are shown in Table 5.2-1 and Figure 5.2-10. Aluminum, silicon, and calcium dominated the release.

Table 5.2-1: Comparison of Total Mass Release in Dissolution Testing by Element

Element	Total Mass Released into Solution (mg)
Fe	3
Zn	3
S	25
Ca	110
Si	393
Al	1634
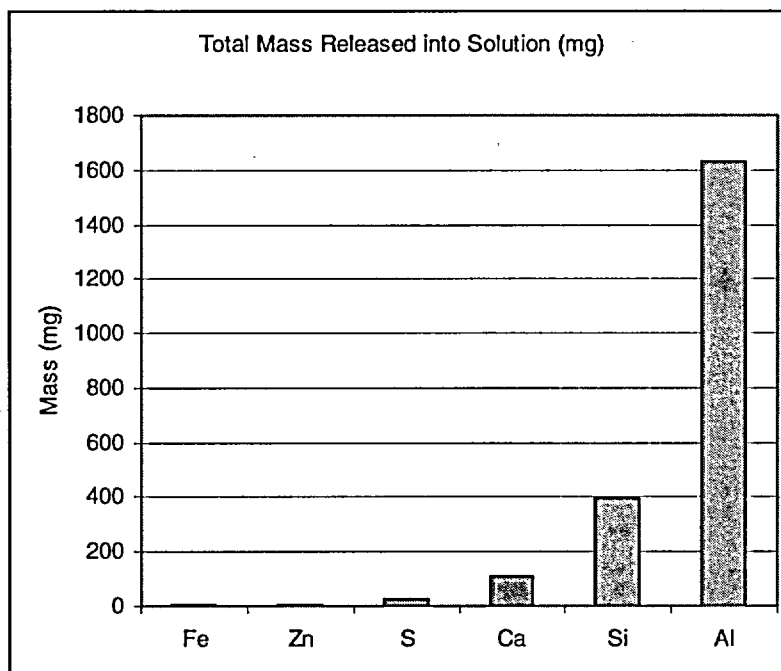
Figure 5.2-10: Comparison of Total Mass Released during Dissolution Testing by Element

The releases from each material were calculated from the test data, and the results are compared in Table 5.2-2 and Figure 5.2-11. It is clear that metallic aluminum has the highest potential for mass release into solution. The concrete release appeared to be relatively high, but the quantity of concrete tested was not scaled to the surface area typically present in PWR containments as were the other materials. This value would have been much lower if had been scaled correctly to the plant survey data provided. Of the insulation materials that were considered, CalSil had the highest potential release and mineral wool the lowest. It is notable that the high density fiberglass released more material than did the Nukon fiberglass.

Table 5.2-2: Comparison of Total Mass Release from the Tested Materials

Material	Total Mass Released into Solution (mg)
Carbon Steel	6
Galvanized Steel	8
Mineral Wool	18
Interam	31
Durablanket	34
Nukon Fiberglass	55
MIN-K	69
High Density Fiberglass	92
CalSil	177
Concrete	376
Aluminum	1580
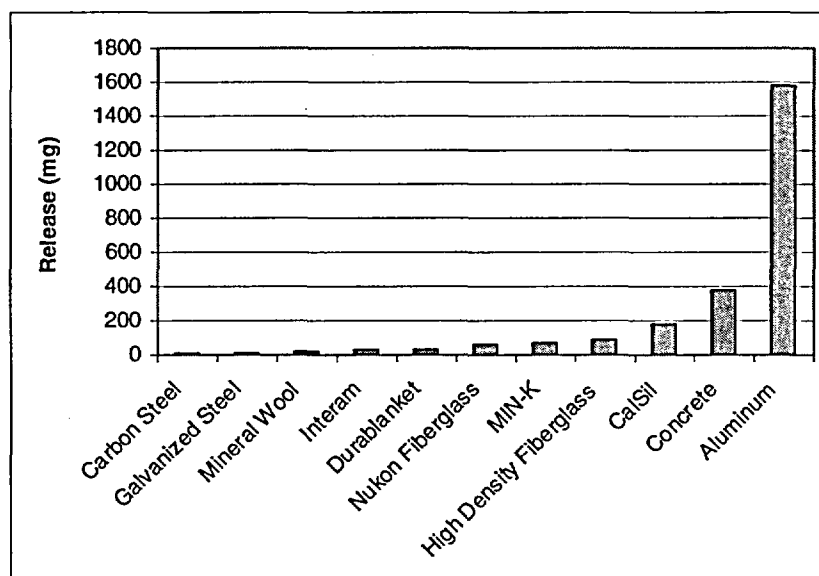
Figure 5.2-11 Comparison of Total Mass Release from the Tested Materials

The variation in calcium and aluminum release with pH was explored. The total Al and the total Ca release was calculated for all design matrix runs at each pH. The values are plotted in Figure 5.2-12. Opposite trends were observed, with more calcium being released at low pH and more aluminum being released at high pH.
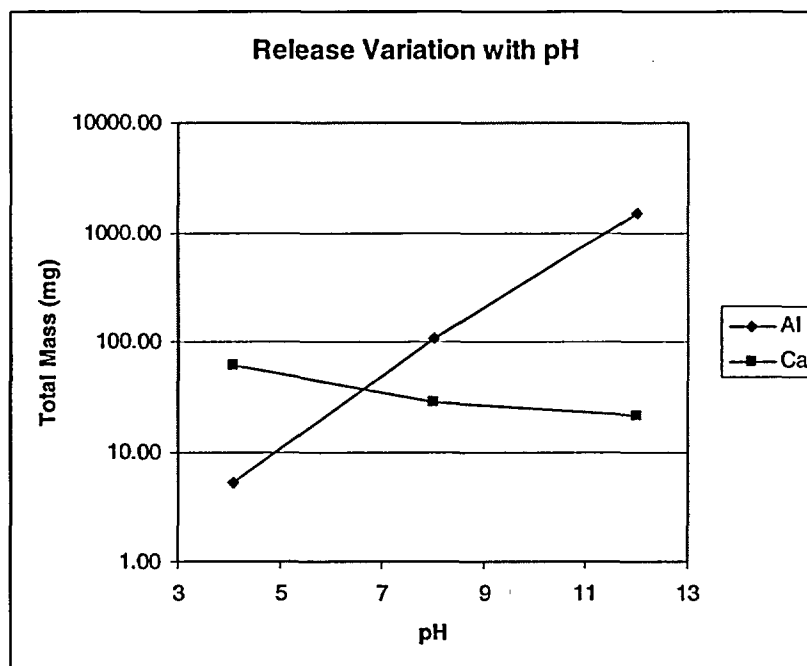
Figure 5.2-12: Total Release of Al and Ca from all Materials over pH Range

5.2.4 Precipitation Tests

5.2.4.1 Test Apparatus and Procedure

At the completion of the 1.5 hour experiments in the reaction vessels, the remaining solutions were pumped into settling cones to measure any precipitation caused by cooling of the dissolved solution. Specifically, the hot test solutions were pumped through small diameter stainless steel cooling lines in a constant temperature water bath and into the settling cones. A timer was started and the material in the settling cones was examined at appropriate intervals. At approximately 30 minutes, cones with any precipitate were noted and photographed. After approximately 1 hour, this process was repeated. After at least 8 hours after the solution was admitted into the settling cone, photographs of the cones were taken, and the presence of any visible precipitates noted.

Figure 5.2-13 shows the settling cones in the water bath. The bath temperature was maintained at 80°F using a combination of heaters and coolers. The small diameter stainless lines used to cool the solution coming from the oven are shown in the background.
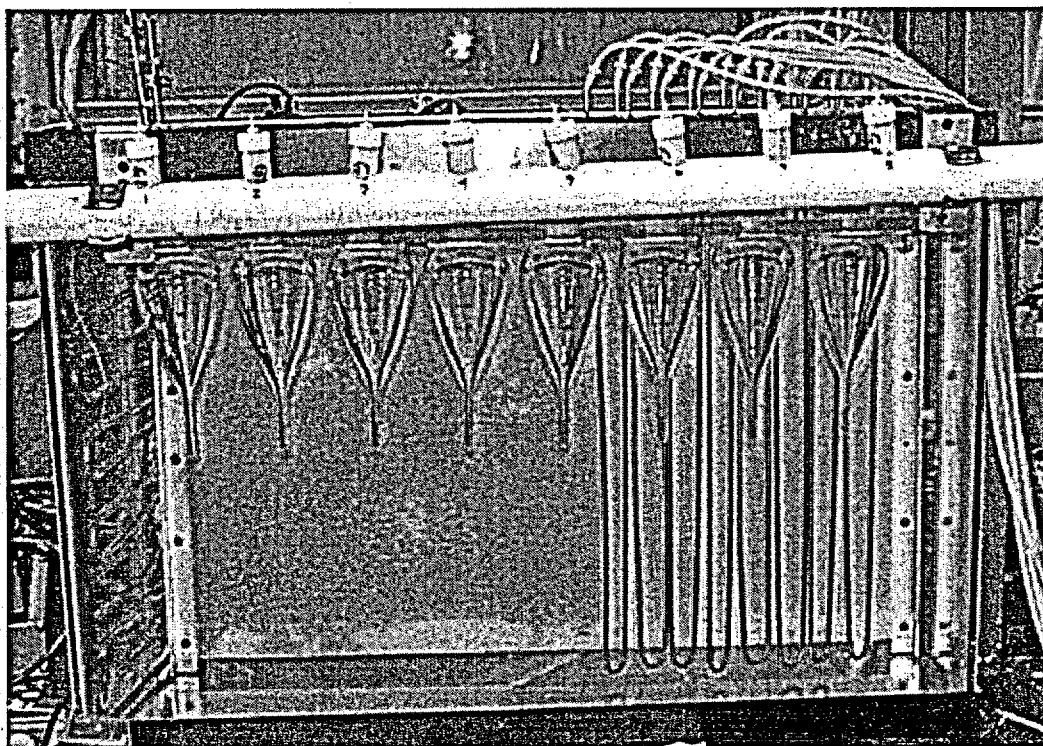
Figure 5.2-13: Solution flowed from the reaction vessels and was cooled in a water bath controlled at 80°F. The solution was sampled and eventually flowed into settling cones in the water bath.

5.2.4.2 Precipitation Test Matrix

The matrix for the precipitations tests performed is shown in Table 5.2-3.

The final precipitation test matrix was developed in consideration of the concentration and identification of the dissolved species detected from dissolution testing. Evaluation of these data indicated that the form and quantity of the key precipitates that would form from species dissolved at elevated pH (>9.0), i.e., sodium aluminum silicate and aluminum oxyhydroxide, would not be fundamentally affected by slight increases in pH. Additionally, the form and quantity would not be expected to fundamentally change as a result of the direction of the change in pH.

Fresh trisodium phosphate was used in all phosphate precipitation tests. Testing on the dissolution rate of aged versus fresh trisodium phosphate showed that aging has only a marginal effect on the dissolution rate of trisodium phosphate[5]. Therefore, the condition of the trisodium phosphate used for precipitation testing would not be expected to have any effect on the quantity and morphology of the phosphate precipitates evaluated in this testing.

Table 5.2-3: Precipitation Test Matrix

PPT Run	Run/ Reaction Vessel	Solution A Dissolution Run	Solution B		Precipitation Method
			Dissolution Run	Buffering Agent	
1	K7	1	-	-	Precipitation from cooling, Al pH 4
2	M7	3	-	-	Precipitation from cooling, Al pH 8
3	S7	5	-	-	Precipitation from cooling, Al pH 12
4	K2	7	-	-	Precipitation from cooling, CalSil, pH 4
5	H2, L2	9	-	-	Precipitation from cooling, CalSil, pH 8
6	M2	11	-	-	Precipitation from cooling, CalSil, pH 12
7	K6	13	-	-	Precipitation from cooling, Nukon, pH4
8	L6	15	-	-	Precipitation from cooling, Nukon, pH 8
9	M6	17	-	-	Precipitation from cooling, Nukon, pH 12
10	K4	19	-	-	Precipitation from cooling, Other Fiberglass, pH 4
11	L4	21	-	-	Precipitation from cooling, Other Fiberglass, pH 8
12	M4	23	-	-	Precipitation from cooling, Other Fiberglass, pH 12
13	K5	25	-	-	Precipitation from cooling, Concrete, pH 4
14	L5	27	-	-	Precipitation from cooling, Concrete, pH 8
15	M5	29	-	-	Precipitation from cooling, Concrete, pH 12
16	K3	31	-	-	Precipitation from cooling, Mineral Wool, pH 4
17	H4, L3	33	-	-	Precipitation from cooling, Mineral Wool, pH 8
18	M3	35	-	-	Precipitation from cooling, Mineral Wool, pH 12
19	K8	37	-	-	Precipitation from cooling, MinK, pH 4
20	M8	39	-	-	Precipitation from cooling, MinK, pH 8
21	L8	41	-	-	Precipitation from cooling, Min K, pH 12

PPT Run	Run/ Reaction Vessel	Solution A Dissolution Run	Solution B Dissolution Run	Solution B Buffering Agent	Precipitation Method
22	O4, K4	43	-	-	Precipitation from cooling, FiberFax, pH 4
23	L1	45	-	-	Precipitation from cooling, FiberFax, pH 8
24	M1	47	-	-	Precipitation from cooling, FiberFax, pH 12
25	O1	49	-	-	Precipitation from cooling, Carbon Steel, pH 4
26	N5	51	-	-	Precipitation from cooling, Carbon Steel, pH 8
27	N1	53	-	-	Precipitation from cooling, Carbon Steel, pH 12
28	O2	55	-	-	Precipitation from cooling, Galvanized, pH 4
29	N6	57	-	-	Precipitation from cooling, Galvanized, pH 8
30	N2	59	-	-	Precipitation from cooling, Galvanized, pH 12
31	O3	61	-	-	Precipitation from cooling, Interam, pH 4
32	N8	63	-	-	Precipitation from cooling, Interam, pH 8
33	N3	65	-	-	Precipitation from cooling, Interam, pH 12
34	K7	1	-	TSP pH 8	PPT of Phosphates, Aluminum
35	K2	7	-	TSP pH 8	PPT of Phosphates, CalSil
36	K6	13	-	TSP pH 8	PPT of Phosphates, Nukon
37	K4	19	-	TSP pH 8	PPT of Phosphates, Other Fiberglass
38	K5	25	-	TSP pH 8	PPT of Phosphates, Powdered Concrete
39	K3	31	-	TSP pH 8	PPT of Phosphates, Mineral Wool
40	K8	37	-	TSP pH 8	PPT of Phosphates, MinK
41	O4	43	-	TSP pH 8	PPT of Phosphates, FiberFax
42	O1	49	-	TSP pH 8	PPT of Phosphates, Steel
43	O2	55	-	TSP pH 8	PPT of Phosphates, Galvanized
44	O3	61	-	TSP pH 8	PPT of Phosphates, Interam
45	K7	1	-	Borax pH 8	PPT of Hydroxides, Aluminum
46	K2	7	-	Borax pH 8	PPT of Hydroxides, CalSil
47	K6	13	-	Borax pH 8	PPT of Hydroxides, Nukon
48	K4	19	-	Borax pH 8	PPT of Hydroxides, Other Fiber Glass
49	K5	25	-	Borax pH 8	PPT of Hydroxides, Concrete
50	M1	31	-	Borax pH 8	PPT of Hydroxides, Mineral Wool
51	K3	37	-	Borax pH 8	PPT of Hydroxides, MinK
52	K8	43	-	Borax pH 8	PPT of Hydroxides, Fiberfax
53	O4	49	-	Borax pH 8	PPT of Hydroxides, Steel
54	O1	55	-	Borax pH 8	PPT of Hydroxides, Galvanized
55	O2	61	-	Borax pH 8	PPT of Hydroxides, Interam
56	O3	8	5	J7 or S7	pH 4, 190°F CalSil with pH 12, 265°F Al
57	E3 or B7	26	5	J7 or S7	pH 4, 190°F Concrete with pH 12, 265°F Al
58	Q1 or E8	26	55	O2	pH 4, 190°F Concrete with pH 4, 265°F Galvanized
59	Q1 or E8	8	50	P1	pH 4, 190°F with pH 4, 190°F Carbon Steel
60	E3 or B7	23	8	E3 or B7	pH 12, 265°F Fiberglass with pH 4, 190°F CalSil

Results of initial precipitate tests, including SEM analysis results, as well as the results of previous evaluations[2], were used to evaluate testing of combinations that were not included in the original test plan. The conclusion of this evaluation was that no additional combinations beyond those considered needed to be tested, on the basis that the quantity of other potential precipitates would be low relative to the quantity of the key precipitates generated (e.g., zinc or other simple metal silicates, or calcium aluminum silicate or other substituted aluminum silicates).

5.2.4.3 Precipitate Formation

Widely varying amounts of precipitate were observed for individual dissolution test experiments. Figure 5.2-14 and Figure 5.2-15 show examples where varying amounts of precipitate were formed. In 25 experiments, measurable quantities of precipitate were formed. The volume of precipitate formed for these cases is shown in Figure 5.2-16.

The data indicates that in the limited cases where precipitates form, the quantity produced can vary quite widely. Table 5.2-4 shows the list of experiments where measurable precipitation occurred. This occurred in 13 of the 60 experiments performed. The mass and volume of the precipitates formed are listed in Table 5.2-4 and the precipitate density estimated.

The masses of precipitates that formed did not correlate well with the total material released, suggesting that considerable dissolved or colloidal material still remained in solution. The original intent of the precipitate mass measurements was to use the ratio of filterable to non-filterable material to reduce the amount of precipitates that would have to be considered in chemical effects screen performance testing. However, the complexity of the precipitation processes observed in this work led to the abandonment of this approach. The precipitation process was in some cases highly time-dependent, and the prediction of the ratio of dissolved and colloidal matter to that of specific precipitates that would form would require consideration of the timing of the addition of each containment material to the coolant, the change in temperature with time, and the degree and order of mixing. The revised approach used in the modeling effort assumed that all aluminum released formed a precipitate and that all calcium in phosphate solutions would precipitate, and so did not use the precipitate masses listed in Table 5.2-4.

A small portion of these precipitates were filtered and the remnant on the filter paper analyzed to attempt to determine the average precipitate composition. The compositions reported from the SEM analyses are listed in Table 5.2-5.
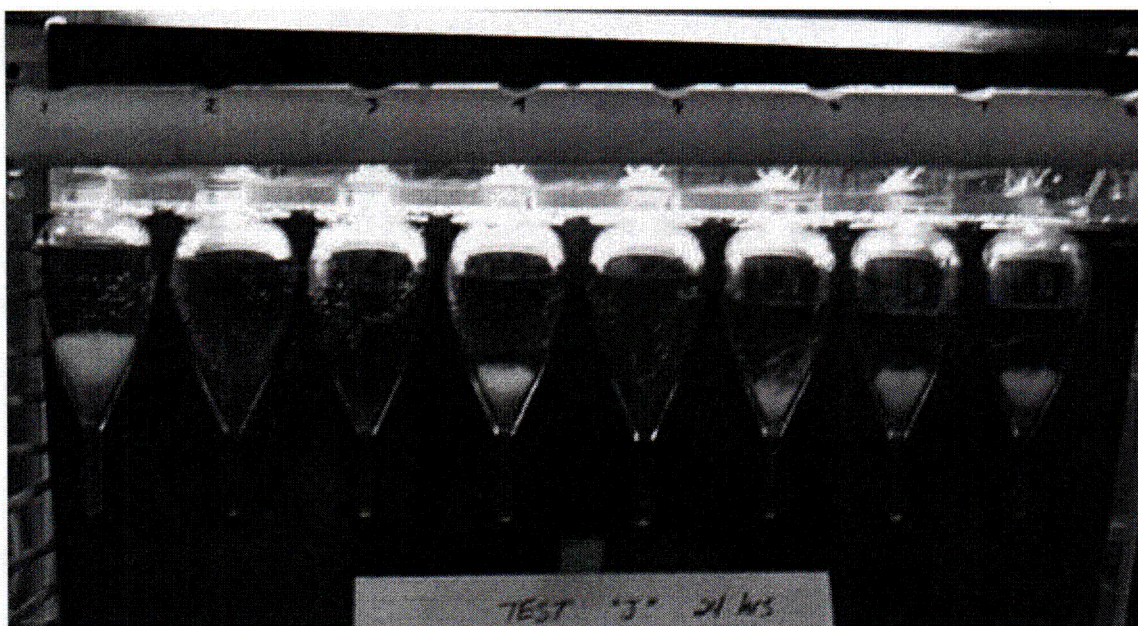
Figure 5.2-14: **Appearance of the settling cones after precipitates formed in the cooled solution. Example of experiments where a significant amount of precipitates were formed.**
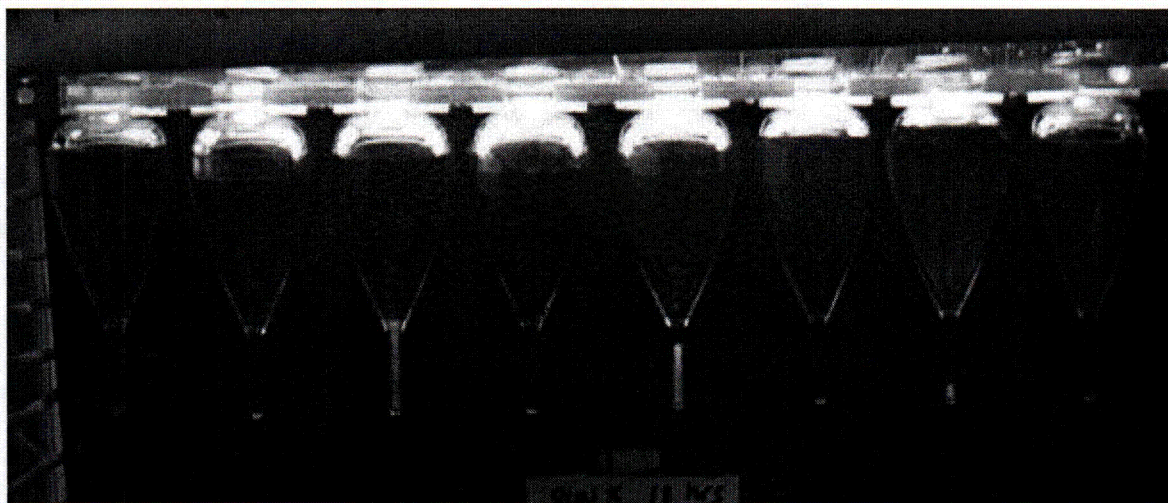
Figure 5.2-15: **Appearance of the settling cones after precipitates formed in the cooled solution. Example of experiments where a moderate amount of precipitates were formed.**

Volume of precipitate observed
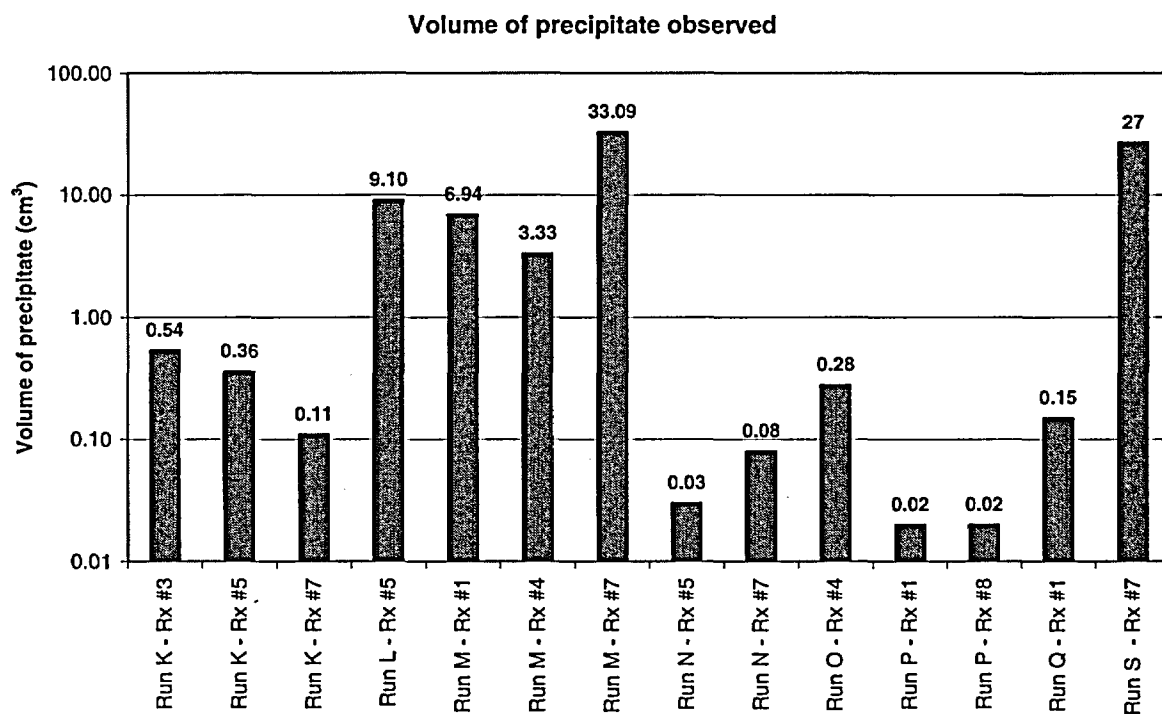
Figure 5.2-16: Volume of Precipitate Observed in the Settling Cones

Table 5.2-4: Experiments with Measurable Amounts of Precipitate

PPT Run	Run/Reactor	Soln A	Soln B	Mass of PPT originally in cone (g)	PPT Total Volume settling cone (cm3)	PPT density (g/cm3)	Notes
1	K7	1	-	0.0016	0.11	0.015	Precipitation from cooling, Al pH 4
2	M7	3	-	0.7548	33.08	0.023	Precipitation from cooling, Al pH 8
3	S7	5	-	0.6154	27	0.023	Precipitation from cooling, Al pH 12
12	M4	23	-	0.0103	3.33	0.003	Precipitation from cooling, Other Fiberglass, pH 12
13	K5	25	-	0.0034	0.36	0.009	Precipitation from cooling, Concrete, pH 4
14	L5	27	-	0.0375	9.1	0.004	Precipitation from cooling, Concrete, pH 8
16	K3	31	-	-0.0008	0.54	--	Precipitation from cooling, Mineral Wool, pH 4
22	O4, K4	43	-	0.0028	0.28	0.010	Precipitation from cooling, FiberFax, pH 4
24	M1	47	-	0.0427	9.94	0.004	Precipitation from cooling, FiberFax, pH 12
30	N2	59	-	0.0045	0.03	0.151	Precipitation from cooling, Galvanized, pH 12
35	K2	7	TSP pH 8	0.0140	n/a		PPT of Phosphates, CalSil
38	K5	25	TSP pH 8	0.0275	n/a		PPT of Phosphates, Powdered Concrete
60	M4		E3 or B7	n/a	n/a		pH 12 265 Fiberglass (high sulfur), with high calcium from pH 4 CalSil

Table 5.2-5: SEM Analysis of the Precipitates

PPT Run	Series/ Reactor	Na	Al	Si	Element (wt%) P	Ca	Cu	Zn	Fe	Mg	Best Guess PPT from Chemistry
1	K7	nd	83.1%	12.2%	nd	nd	4.7%	nd	nd	nd	Hydrated AlOOH
2	M7	2.0%	95.2%	0.0%	nd	nd	2.8%	nd	nd	nd	Hydrated AlOOH
3	S7	3.4%	96.6%	nd	nd	nd	nd	nd	nd	nd	Hydrated AlOOH
12	M4	17.3%	26.9%	53.5%	nd	2.3%	nd	nd	nd	nd	$NaAlSi_3O_8$ with minor calcium aluminum silicate
13	K5	0.5%	74.4%	16.1%	nd	4.9%	4.1%	nd	nd	nd	Calcium aluminum silicate of some type- Al rich
14	L5	0.8%	41.6%	27.0%	nd	24.1%	5.6%	nd	0.8%	nd	Calcium aluminum silicate of some type
16	K3	0.5%	79.6%	12.7%	nd	0.1%	7.1%	nd	nd	nd	Hydrated AlOOH
22	D4	nd	85.0%	7.9%	nd	nd	7.2%	nd	nd	nd	Hydrated AlOOH
24	M1	25.3%	29.1%	38.8%	nd	nd	6.8%	nd	nd	nd	$NaAlSi_3O_8$
30	N2	nd	1.1%	17.0%	nd	2.4%	3.7%	75.9%	nd	nd	Zn_2SiO_4 (Willemite) with Ca and Al impurities
35	K2	nd	1.1%	23.5%	27.1%	43.2%	5.1%	nd	nd	nd	Calcium phosphate and a silicate
38	K5	nd	4.5%	1.0%	35.9%	54.8%	3.2%	nd	nd	0.7%	Calcium phosphate with AlOOH
60	M4	13.3%	11.1%	50.3%	nd	16.6%	8.8%	nd	nd	nd	Sodium calcium aluminum silicate

5.2.5   References

5.2-1   J. Oras, J. H. Park, K. Kasza, K. Natesan, and W. J. Shack, "Chemical Effects/Head-Loss Testing Quick Look Report, Tests 1&2, September 16, 2005, NRC IN 2005-26 PT2.

5.2-2   V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

5.2-3   J. C. Griess and A. L. Bacarella, "Design Considerations of Reactor Containment Spray Systems-Part III. "The Corrosion of Materials in Spray Solutions", Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.

5.2-4   PWR Primary Water Chemistry Guidelines: Volume 2, Revision 5, EPRI, Palo Alto, CA: 2003. TR-105714-V2R5.

5.2-5   J. L. Wilken, Omaha Public Power District letter to R. C. Young, U. S. Atomic Energy Commission, dated November 14, 1973.

5.3   PRECIPITATE CHARACTERIZATION

5.3.1   Measured Settling Rates of Precipitates

The precipitates formed both by cooling and by combining solutions were placed in centrifuge tubes in order to determine their settling rates. After shaking each solution containing precipitate, approximately 10 ml was transferred into a centrifuge tube. The visible volume of precipitate, i.e. the volume up to where the solution appeared clear in the centrifuge tube, was then recorded at 15 min, 1 hr, 2 hr, 3 hr, and 4 hr. Table 5.3-1 presents these recorded settling rates for each precipitate formed.

As can be inferred from the settling rates presented in the table below, the precipitates formed do not settle quickly and thus cannot be discounted as a concern for sump screen performance. Note that since these are hindered settling rates, i.e., the fall of particles may be hindered due to their interaction with neighboring particles, a determination of particle size cannot be made from the data.

Table 5.3-1: Measured Settling Rates of Formed Precipitates

PPT Run	Start Volume (ml)	Volume of PPT (ml)					Average Settling Rate (mm/hr)	Note
		15 min	1 hr	2 hr	3 hr	4 hr		
1	10.2	ND	ND	ND	ND	0.01	ND	Precipitation from cooling, Al pH 4
2	10.2	10.1	9.8	9.0	8.5	7.1	9	Precipitation from cooling, Al pH 8
3	10.3	10.2	9.8	9	8.5	7.4	3	Precipitation from cooling, Al pH 12
12	10.1	ND	0.05	0.3	0.25	0.3	62	Precipitation from cooling, Other Fiberglass, pH 12
13	10.2	ND	ND	9.6	9.5	0.3	2 or 15	Precipitation from cooling, Concrete, pH 4
14	10.4	10.0	9.7	6.5/.02	0.04	0.02	5 or 32	Precipitation from cooling, Concrete, pH 8
16	10.2	ND	ND	ND	ND	0.02	ND	Precipitation from cooling, Mineral Wool, pH 4
22	10.2	ND	ND	ND	ND	ND	ND	Precipitation from cooling, FiberFax, pH 4
24	10.2	0.3	0.6	0.7	0.7	0.7	124	Precipitation from cooling, FiberFax, pH 12
30	10.1	ND	ND	ND	0.01	0.02	ND	Precipitation from cooling, Galvanized, pH 12
35	10.3	0.4	0.3	0.3	0.3	0.3	124	PPT of Phosphates, CalSil
38	10.4	2.5	1.8	1.5	1.4	0.8	99	PPT of Phosphates, Powdered Concrete
60	9.8	9.8	0.4	0.4	0.4	0.5	59	pH 12, 265°F Fiberglass + pH 4, 190°F CalSil

5.3.2 Estimation of Precipitate Size

SEM analyses were performed on the thirteen precipitates formed during bench testing in order to estimate the size of each precipitate's constituent particles. The high magnification pictures are included in Appendix B. These pictures demonstrate that either the constituent particles are less than 20 μm or the larger agglomerated particles are approximately 20 μm, and so their constituent particles must be less than 20 μm. As can be concluded from the pictures attached in Appendix B and from literature, the types of precipitates generated from the reaction of dissolved containment materials tend to flocculate, resulting in agglomerated particles with sizes in the range of 10 to 100 μm. These particles are comprised of primary particles (flocculi) of submicron size, and will likely break up under shear[1,2].

5.3.3 References

5.3-1   Biggs, C. A. and Lant, P. A., "On-Line Determination of Floc Size and the Effect of Shear," Water Research, 34(9), June 2000.

5.3-2   Jarvis, P., Jefferson, B. and Parsons, S., "Measuring Floc Structural Characteristics," Reviews in Environmental Science and Biotechnology. Vol 4 (1-2), May 2005.

5.4   PRECIPITATE FILTERABILITY TESTS

5.4.1   Summary

Precipitate filterability tests were carried out at the Westinghouse Science and Technology Department to determine the filter cake coefficients for the various precipitates produced in the chemical effects bench testing discussed in Section 5.2. The results of these tests indicated that chemically induced precipitates produced solids with filtration constants (average = 0.415+/-0.548) about half that of the Si and Al precipitates (0.788+/-0.501) formed on cooling. This indication comes from a relatively limited dataset and so needs to be used with care. However, the lower values could be used as an initial guess for calculating pressure drops.

5.4.2   Filtration Model

The data obtained from this experiment was modeled using the following equation:

$$F = (K_{fx} / m_x) * A * dP / n \qquad \text{Equation 5-1}$$

Where:

F = specific flow rate (gpm/ft^2)

K_{fx} = filter solids constant for a specific precipitate or solid x (gpm/ft^6/psi*lb*cP)

dP = measured pressure drop across filter with solids (psi or lb$_f$/in^2)

n = viscosity of the liquid in the slurry (assumed to be water) (cP)

m_x = specific dry (1 hour @ 110°C) solids x loading (lb/ft^2)

A = flow area (ft^2)

This model makes the assumption that the filter cakes are relatively thin and incompressible. This assumption was made since the applied pressure drops will be very small (on the order of 1 to 6 psi). Note that this assumption was supported by the data in that all the pressure versus flow plots obtained experimentally were reasonably linear in the low delta P regions.

To apply this test data to calculations for screen pressure drops, the following data is required:

1. The method of bed formation, i.e., whether the bed is formed from a mix of solids or formed by layering of various solids

2. Specific dry (1 hour @ 110°C) weight of each solid (lb/ft^2)

3. Either the temperature to determine the viscosity if water is assumed or the measured liquid (not slurry) viscosity

4. The K_{fs} of the screen (gpm/ft^4/psi*cP) determined with the viscosity at the temperature of interest

5. Flow rate (gpm/ft^2)

If the bed is formed in layers, then the overall K_f can be determined analogous to the method used to determine an overall heat transfer coefficient. That is:

$$1/K_f = 1/K_{fs} + \Sigma \, m_x/K_{fx} \qquad \text{Equation 5-2}$$

Where:

K_{fs} = the screen coefficient (gpm/ft^4/psi*cP)

m_x = specific mass of each solid (lb/ft^2)

K_{fx} = filter solids constant for a specific precipitate x (gpm/ft^6/psi*lb*cP)

A simple mass-weighed approach may be used as a theoretical means to determine the effective K_f for a mix of solids as opposed to a single solid.

$$K_{fz} = \Sigma \, K_{fx} \, / \, m_x \qquad \text{Equation 5-3}$$

where K_{fz} is the effective K_f for the mixed solids bed.

This K_{fz} can then be used along with the screen K_{fs} in the equation below to determine the overall K_f.

$$1/K_f = 1/K_{fs} + 1/K_{fz} \qquad \text{Equation 5-4}$$

Finally, K_f can then be used to determine the pressure drop using the equation:

$$dP = F \, / \, (K_f * A \, / \, n) \qquad \text{Equation 5-5}$$

5.4.3   Test Procedure

After forming precipitates in the first portion of testing described in Section 5.2, the precipitates were then tested in a filter apparatus to determine their filterability coefficient using the procedure given below and the apparatus shown in Figure 5.4-1. The solution containing the precipitate was pumped through a filter at different flow rates in order to record the pressure drop at each flow rate. The filtration experiments were done at room temperature (between 70°F and 78°F).

<u>Equipment List</u>

- 4-Channel Peristaltic Pump, Pump Head Cole Parmer EW-07519-10 with cartridges Cole-Parmer EW-07519-85 and pump tubing EW-06508-14
- Pressure sensor 1- Omega PX303-0 0A10V 0-50 psia
- Pressure sensor 1- Omega PX303-050A5V 0-50 psia
- Flow sensor- McMillan Co 104 Flo-Sen S/N 1011 3
- Tubing outside pump- Cole-Parmer L/S 14 Tubing, C-96410-14
- Filter Holder-25 mm Filter Holder VWR 28144-164
- Filter – 25 mm glass fiber filter, 1-micron, 28150-134

<u>Preparation</u>

- Calibrate the program in order to obtain pump flow rates. Three flow rates are used in order to determine the change in pressure drop with flow rate.
- Select a 1-micron glass fiber filter and weigh it to the nearest 0.0001 g.
- Place the fiber filter in the holder.
- Measure 75 ml of 4400 ppm boron solution into settling cone.
- Place the dip tube and the return line in the settling cone.

<u>Filtration</u>

- Turn on the pump and set flow rate to the highest flow rate in order to load the filter at the beginning of the test.
- Allow sufficient time for the flow to stabilize through the filter (5 minutes). Then thoroughly shake the solution containing precipitate and add approximately 10 ml to the settling cone.
- Record pressure drop across filter with time.
- After the total solution volume has passed through the filter about four times, decrease the pump flow rate.
- Record pressure drop with time.

- After the total solution volume has passed through the filter about four times, again decrease the pump flow rate.

- Record the pressure drop with time, until approximately another 4 solution volumes have passed through the filter.

End of Experiment Tasks

- Rinse the filter with 10 ml of deionized water.

- Dry the filter at 110°C +/- 10°C for 1 hour.

- Weigh the filter.

- Place filter in a labeled container for later SEM analysis.

- Clean loop before next test with a flow of deionized water.

Figure 5.4-1: Filter Test Equipment Schematic
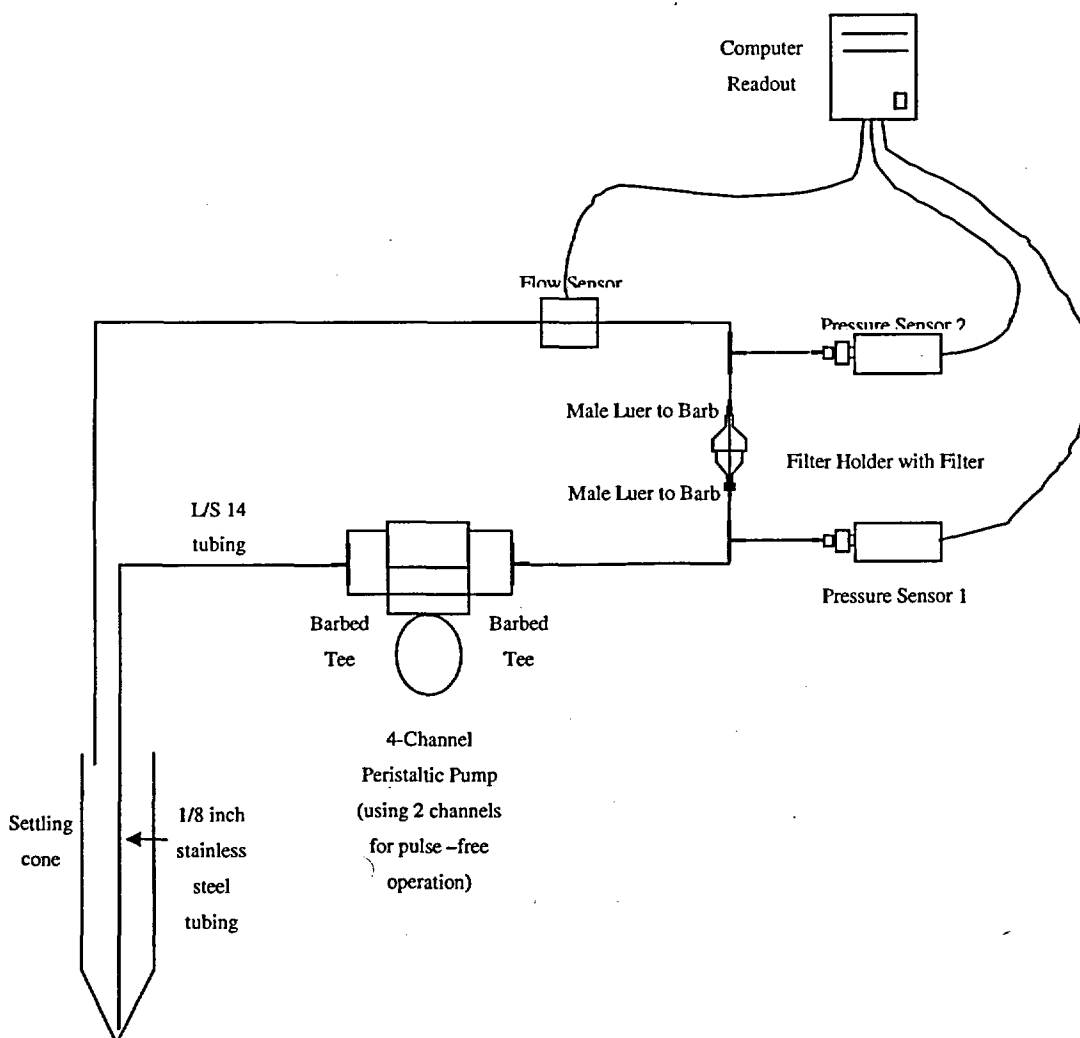
The experimental data obtained were:

f = flow rate (ml/min) as a function of dP (psi)

n = water viscosity (cP) from the temperature (°F)

m = dry (110°C @ 1 hour) solids (gm)

A = 3.8 cm^2 measured exposed filter area

A representative figure containing the dP versus flow rate data recorded as a function of time is presented below. Similar data is available for all of the runs conducted in order to gauge the filterability of the precipitates.
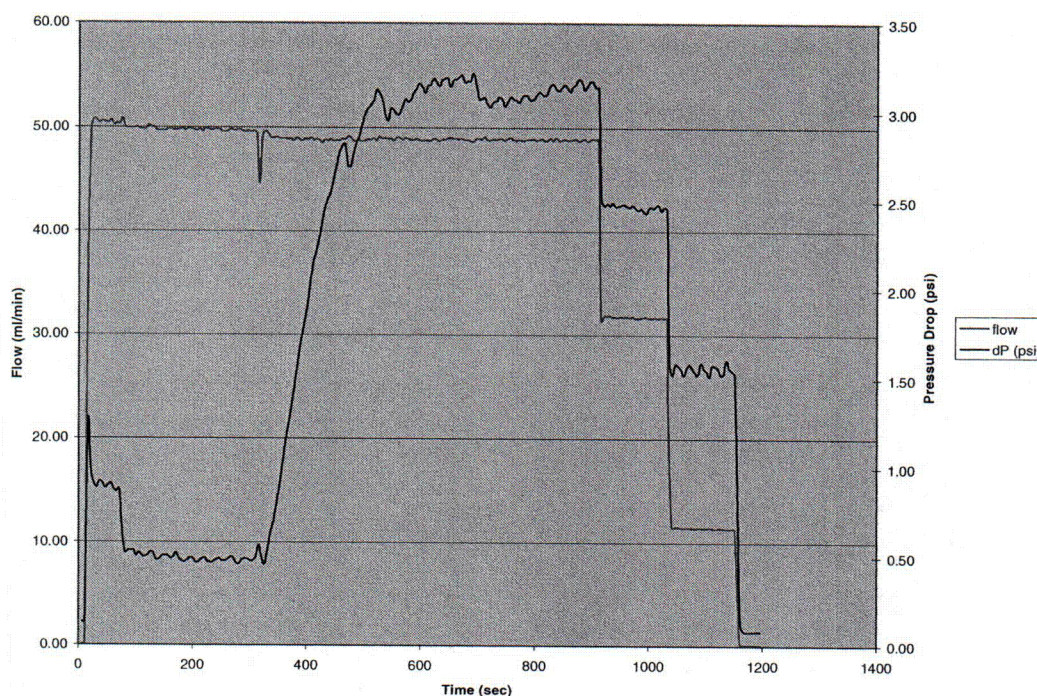
Figure 5.4-2: dP and Flow Rate as a Function of Time for PPT 24D

Graphs of the dP versus flow rate (ml/min) are shown in Appendix C. Each set of data was analyzed in the linear portion using least squared regression analysis to obtain the slope of the curve (z in psi-min/ml). Note that some curves bent over, i.e., the flow increased with little or no increase in pressure drop. The higher flow data from these tests was not used since the upper flow data was likely taken before the solids had finished depositing on the filter. Also, some near-zero point data was not used since at very low delta P values, there were instabilities in some of the delta P measurements. The range of data that was used from each test is indicated on the data plots given in Appendix C. This slope was then combined with the water viscosity, solids weight and effective filter area to determine the overall (filter + cake) K$_f$ using the equation:

$$K_f = n / A^2 / z / [3785 \text{ ml/gal}] * [929 \text{ cm}^2/\text{ft}^2]^2 \qquad \text{Equation 5-6}$$

The K_{fs} (filter constant for the filter (gpm/ft^4/psi*cP)) was obtained from the slope (zs) of the dP versus flow measurement for the filter (Figure C-1) using the equation:

$$K_{fs} = n / A^2 / zs / [3785 \text{ ml/gal}] * [929 \text{ cm}^2/\text{ft}^2]^2 \qquad \text{Equation 5-7}$$

Note that by using the slope, it was assumed that the pressure versus flow data passed through the point 0,0. The K_{fx} (filter solids constant for a specific precipitate (gpm/ft^6/psi*lb*cP) was then obtained by substituting Equation 5-7 into Equation 5-2 and solving the resulting equation for K_{fx}:

$$m / A / K_{fx} / [454 \text{ gm/lb}] * [929 \text{ cm}^2/\text{ft}^2] = 1/K_f - 1/K_{fs} \qquad \text{Equation 5-8}$$

Note that the K_{fs} was corrected to the viscosity at the temperature at which each filtration test was run.

5.4.4 Results

The results from these tests are summarized in Table 5.4-1. The dP versus flow data is presented for each run in Appendix C. These results indicate that the K_{fx} for the various precipitates range from 0.028 to 1.621 after discounting results from those PPT tests that had too little precipitate to result in a discernible dP measurement: PPT runs 1, 13, 14, 16, 22 and 30.

For PPT runs 1, 14, and 16, the dP vs. flow data indicate that the head loss with debris laden filters is comparable to or less than the clean filter head loss. This anomaly may be attributed to either some bypass of the filter or slight errors in the pressure measurements which could cause a negative number when the difference of two small numbers is determined.

The remaining PPT runs are listed below.

Table 5.4-1: Precipitate Filter Coefficients

PPT Run	Precipitation Formation Method	Filter Coefficients
2	PPT on cooling, Al pH 8	$K_{fx} = 0.818$
3	PPT on cooling, Al pH 12	$K_{fx} = 0.209$
12	PPT on cooling, Other Fiberglass, pH 12	$K_{fx} = 0.195$
24a	PPT on cooling, FiberFrax, pH 12	$K_{fx} = 1.621$
24b	PPT on cooling, FiberFrax, pH 12	$K_{fx} = 1.069$
24c	PPT on cooling, FiberFrax, pH 12	$K_{fx} = 0.653$
24d	PPT on cooling, FiberFrax, pH 12	$K_{fx} = 0.953$
35	PPT of Phosphates, CalSil	$K_{fx} = 0.803$
38	PPT of Phosphates, Powdered Concrete	$K_{fx} = 0.028$
60	pH 12, 265 Fiberglass (high sulfur), with high calcium from pH 4 CalSil.	$K_{fx} = 0.401$

This data indicates that:

1. Phosphates cause precipitation by super saturation at temperature and have low filtration constants (average = 0.415+/-0.548). The other precipitate, PPT 60, has a similar filtration constant (0.401). The large uncertainty of the results is due to the limited number of phosphate precipitation runs for which a filtration coefficient may be developed.

2. The Si and Al precipitates formed on cooling have relatively high filtration constants (0.20 to 1.6, average = 0.788+/-0.501).

3. The repeated PPT24 runs had an average of 1.07+/- 0.453 with the range of 0.653 to 1.62. This is about the same as the entire set of data (average = 0.675+/-0.484).

6.0 CHEMICAL MODEL

6.1 INTRODUCTION

The results of this test program, consistent with previous work such as the ICET program, show that the predominant chemical precipitates are aluminum oxyhydroxide, sodium aluminum silicate and calcium phosphate (for plants using trisodium phosphate for pH control). Other minor silicate materials may also be generated (e.g., calcium aluminum silicate or zinc silicate), but the contribution of these materials is expected to be small relative to the predominant precipitates (i.e., less than 5 percent). On this basis, the chemical model considers only the release rates of aluminum, calcium and silicate. Other chemical species may be ignored. A more detailed justification for eliminating zinc and iron materials is included in Sections 6.2.2 and 6.2.3, respectively. The reason for not considering nickel and copper based materials is given in Section 5.1.2, "Containment Materials".

The primary source of aluminum is from corrosion of aluminum alloys present in coatings, structural members and in components such as valves and instrument blocks. A minor aluminum contribution results from dissolution of aluminum silicate and other aluminum bearing minerals in insulation (e.g., Durablanket or mineral wool) and concrete. The release rate of aluminum from aluminum alloys is fairly constant over time for a given set of chemistry and temperature conditions. The release rate of aluminum from these materials decreases with time as the applicable solubility limit is approached. Additionally, the release rate from aluminum silicate insulation materials decreases with increasing concentration of dissolved aluminum from all sources due to the common ion effect. It should be noted that aluminum corrosion is not affected by the mode of solution exposure[1], so there is no need to develop different modeling equations for aluminum that is submerged in the sump pool and for aluminum exposed only to the containment spray solution.

The primary sources of calcium are concrete and calcium silicate insulation. Minor contributors include fiberglass and mineral wools. As with aluminum from aluminum-bearing minerals, the release rate of calcium from these materials decreases with time as the solubility limit is approached.

It should be noted that silicate is recognized as an effective inhibitor for corrosion of aluminum alloys[2]. This effect was observed during selected testing performed as part of the ICET program. Evaluation of this effect was not performed as part of this single-effect test program, and is therefore not explicitly included in the current model. This adds some degree of conservatism to the model. The exact degree of conservatism is a function of the conditions under which the bulk of the aluminum release occurs. For example, aluminum release from non-submerged aluminum would not be affected, nor would aluminum release that occurs prior to significant release of silicate.

6.1.1 References

6.1-1   J. C. Griess and A. L. Bacarello, "Design considerations of Reactor Containment Spray Systems- Part III. The Corrosion of Materials in Spray Solutions," Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.

6.1-2   Revie, R. Winston, ed. Uhlig's Corrosion Handbook (2nd Edition). John Wiley & Sons, 2000.

6.2   DETERMINATION OF RELEASE RATE EQUATIONS

For each chemical species, concentration data generated during bench testing at specific chemistry conditions were used in a regression analysis to develop release rate equations as a function of temperature, pH, and the concentration of that species. Equations were developed for each predominant source material for each chemical species. For example, different functions were used to calculate calcium release from calcium silicate and concrete.

6.2.1   Metallic Aluminum

The release rate data for aluminum metal was much different from that of the insulation materials. The release rate increases dramatically as the pH was increased above 8 and release rates were especially high at 265°F. The fitting function that was used to describe the aluminum release is shown in Equation 6-1:

$$RR = 10^{[A + B(pHa) + C(1000/T) + D(pHa)^2 + E(pHa)(T)/1000]} \qquad \text{Equation 6-1}$$

where:

     RR = release rate in mg/(m^2 min)

     $A = -4.049$

     $B = 0.4371$

     $C = 0.7172$

     $D = -0.024398$

     $E = 3.065$

     pHa = initial pH corrected to 25°C

     T = temperature (°K)

This equation was developed by using multiple linear regression to fit experimental log(RR) values. The form of the equation was selected empirically by fitting several different equations to the data and comparing the goodness of fit. A good fit to the experimental data was obtained for Equation 6-1 with all terms being significant ($p < 0.05$) except for B ($p = 0.13$). The fit of the model to the experimental data is shown in Figure 6.2-1.
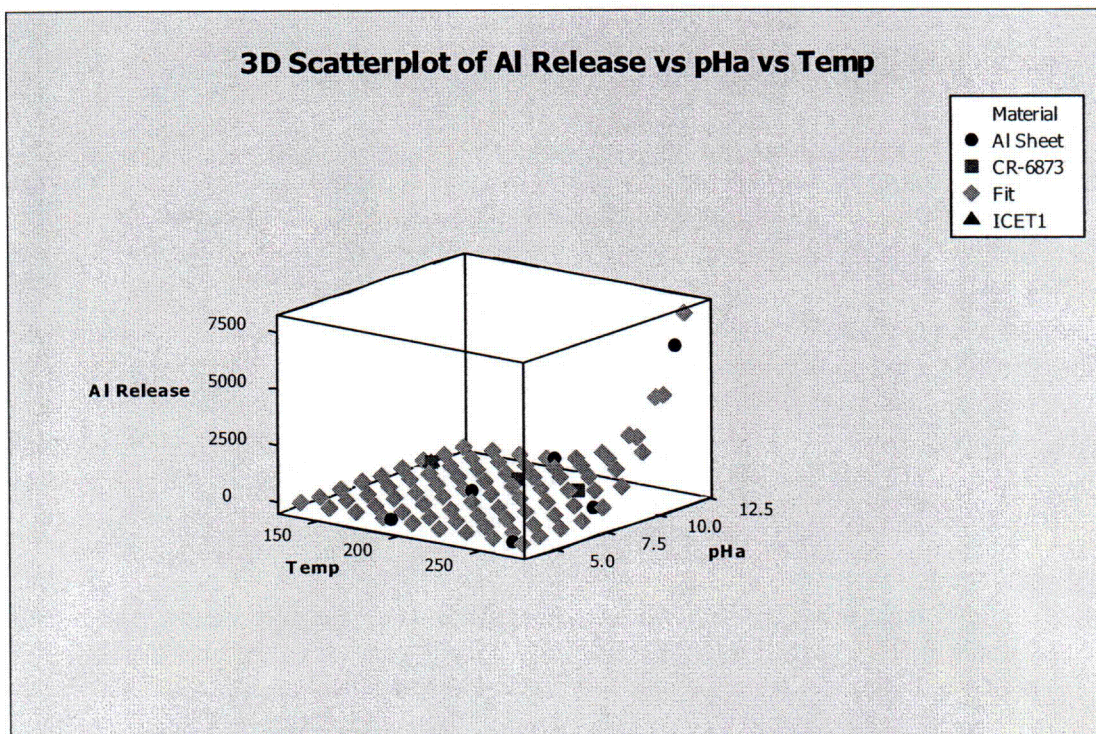
Figure 6.2-1: Predicted Al Release Using Equation 6-1 Compared to Experimental Data from the Program (Al Sheet) and Reference Data (Temperature in Units of °F).

There was some initial concern that the corrosion rates measured for aluminum in this work were erroneously high and that the model predicted excessive corrosion releases. The release rates predicted using Equation 6-1 were about ten times higher that the actual release rate measured in ICET Test 1[1] and those measured by Jain et. al.[2]

Because of the concern that the aluminum release rates were too high, several longer dissolution tests were done at intermediate pH values. Also, additional literature data was obtained from Oak Ridge [3]. The Oak Ridge data for aluminum Alloy 1100 corrosion was consistent with that obtained in the dissolution testing. Furthermore, the longer-term release data (1 day) measured at 190°F and pH 9.4 and 10.0 were consistent with that obtained in the dissolution tests. The results of the bench scale dissolution tests, the longer-term tests, and the Oak Ridge data are compared in Figure 6.2-2. There was no indication that the release rate changed significantly from 90 min to 4 hours to 20 hours since the corrosion rates calculated for these time periods were very similar. Therefore, it is reasonable to conclude that the bench test dissolution rates and Equation 6-1 are accurate.

Aluminum Corrosion Rate In Boric Acid Solutions

10000.0

$y = 6.61E+05e^{-2.32E+00x}$

1000.0

Corrosion Rate (mg/dm²/h)

$y = 1.58E+13e^{-9.42E+00x}$

100.0

$y = 1.38E+11e^{-8.06E+00x}$

10.0

$y = 4.59E+16e^{-1.35E+01x}$

1.0

2.4   2.5   2.6   2.7   2.8   2.9   3.0

1000/T (K)

◆ pH 11.8	■ pH 8.1	▲ pH 4.7	■ ORNL pH 9.3
X pH 10	● pH 9.3	Expon. (pH 11.8)	Expon. (pH 8.1)
Expon. (pH 4.7)	Expon. (ORNL pH 9.3)		
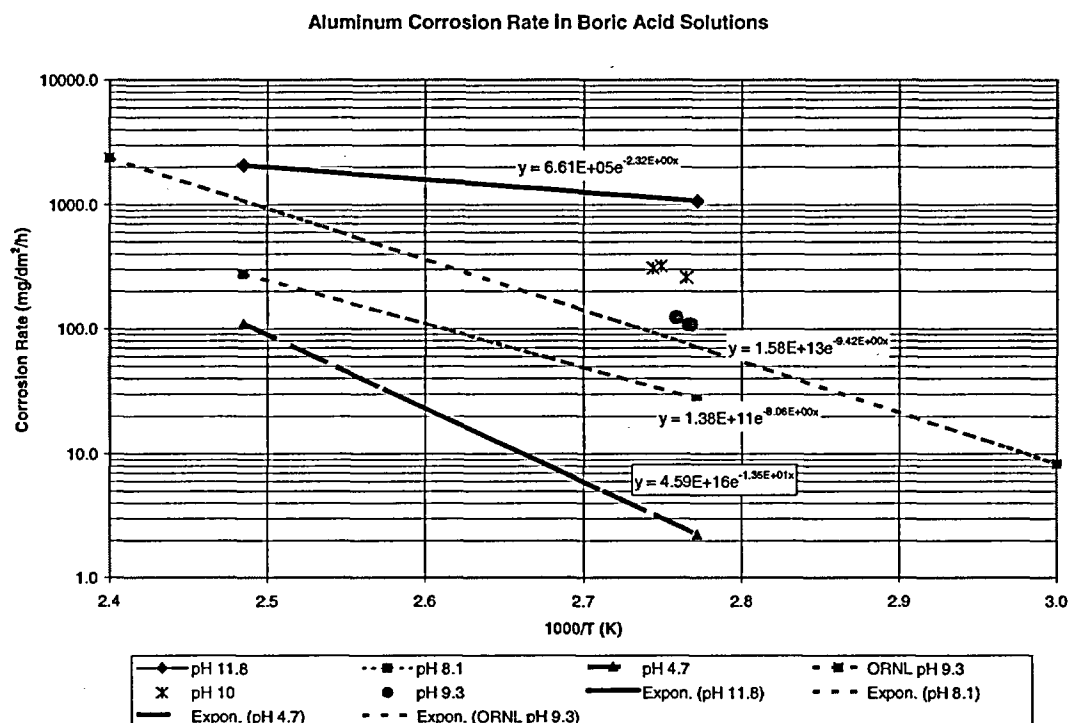
Figure 6.2-2: Corrosion Release for Aluminum Alloy 1100: Bench Test Data Compared to Oak Ridge Data

Aluminum corrosion data from WCAP-7153A[4] is often used in safety analyses concerned with post-LOCA containment hydrogen generation, so this data was also compared to the bench test data. The corrosion rates in WCAP-7153A had greater pH dependence than the bench test corrosion rates with the WCAP-7153A data bracketing the bench test data.

The aluminum model was refined by inclusion of literature data within the data set and repeating the fitting process. This was done primarily to improve model predictions at temperatures below the range covered by the bench scale testing. The literature data included in the model is shown below in Table 6.2-1. Equation 6-2 gives the results of the fit.

Table 6.2-1: Data Used in Aluminum Corrosion Model

Source	Label	Temperature (°F)	pH	Corr. Rate/Area (mg/m2-min)
Bench Test	Al Sheet	190	4.1	9.29
Bench Test	Al Sheet	190	8	44.7
Bench Test	Al Sheet	190	12	1001
Bench Test	Al Sheet	265	4.1	89.4
Bench Test	Al Sheet	265	8	395
Bench Test	Al Sheet	265	12	3338
Oak Ridge A1100 Runs (2)	CR-6873	140	10	16.4
Oak Ridge A1100 Runs (2)	CR-6873	194	10	31.5
Oak Ridge A1100 Runs (2)	CR-6873	230	10	36.7
ICET 1 Average (1)	ICET1	140	10	12.2
WCAP 7153A A1100 Runs (3)	Al coupon	210	7	1.30
WCAP 7153A A1100 Runs (3)	Al coupon	210	8	12.2
WCAP 7153A A1100 Runs (3)	Al coupon	210	9	216
WCAP 7153A A1100 Runs (3)	Al coupon	210	10	6076

$$RR = 10^{[A + C(1000/T) + D(pHa)^2 + E(pHa)(T)/1000]} \qquad \text{Equation 6-2}$$

where:

RR = release rate in mg/(m^2 min)

$A = 14.69039$

$C = -4.64537$

$D = 0.044554$

$E = -1.20131$

pHa = initial pH corrected to 25°C

T = temperature (°K)

The fit to the combined data set was much poorer than the fit to the bench test aluminum data alone as would be expected since the materials and methods used to determine the corrosion rates varied from laboratory to laboratory. The multiple R-squared value was 0.77. The p-value for the "A" coefficient was 0.05, and the values for C, D, and E were 0.04, 0.20 and 0.40, respectively. The "B" coefficient from the linear pHa term, was dropped since its inclusion decreased the adjusted R-squared obtained for the regression.

The fit of the data to the predictions of Equation 6-2 are shown in Figure 6.2-3. The predicted values are displayed on a log scale. It is clear that the WCAP-7153A data labeled "Al coupon" shows a stronger pH dependence than the corrosion data from other sources. The other corrosion data all appears to be part of the same population and was fit reasonably well with Equation 6-2.
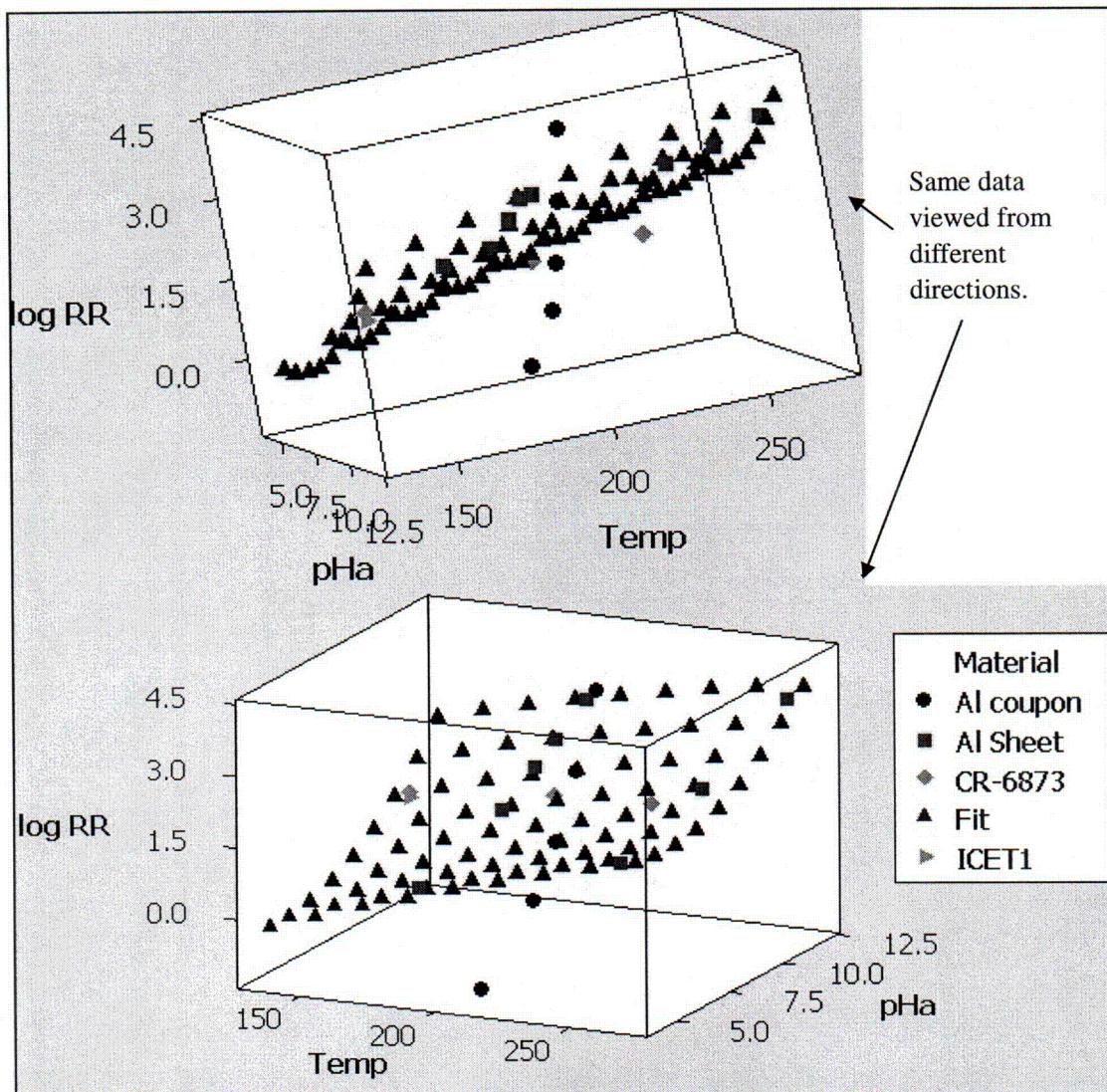
Figure 6.2-3: Fit of Equation 6-2 to Experimental Aluminum Alloy 1100 Corrosion Data

It is suggested that Equation 6-2 be used in chemical effects modeling since it was developed using a wider range of input data than Equation 6-1.

6.2.2 Galvanized Steel

A function was fit to the bench test zinc release rate data so the corrosion of galvanized steel material and other materials containing metallic zinc could be modeled. The form of the equation was the same as for the aluminum model.

$$RR=10[A + B(pHa) + C(1000/T) + D(pHa)^2 + E(pHa)(T)/1000] \qquad \text{Equation 6-3}$$

where:

RR = release rate in mg/(m^2 min)

A = -15.10693334

B = -3.670953896

C = 0.103589245

D = 7.303961651

E = 5.485050709

pHa = initial pH corrected to 25°C

T = temperature (°K)

The zinc release rates were predicted at 10 different PWRs using utility supplied pH-time curves and either utility-supplied or generic containment temperature profiles. The plants had a variety of pH control agents. The exposed zinc surface areas were as high as 325,215 square feet. It was assumed un-submerged material did not contribute to zinc releases after termination of the spray phase. The integrated zinc mass releases are given in Table 6.2-2.

Table 6.2-2: Predicted Integrated Zinc Release for 30 Days Post-LOCA

Plant Code	Buffer	Zn Release from Unsubmerged Material (kg)	Zn Released from Submerged Material (kg)
G	TSP	0.646	3.29
C	Borax	0.168	6.115
·F	TSP	0.258	3.991
E	NaOH	0.019	0.263
D	NaOH	0.578	0.304
A	TSP	0.134	3.711
J	Borax	0.855	0.136
I	NaOH	0.047	0.191
B	TSP	0.006	3.824
H	NaOH	0.07	0.758

The zinc releases were relatively small and can be ignored in chemical effects precipitation modeling.

6.2.3   Uncoated Steel

The release rates for iron from uncoated steel in the bench tests were on the same order as the zinc release rates, so iron can also be ignored in chemical effects precipitation modeling.

6.2.4 Silicates

All of the insulation materials contain silicates as major components. It has been shown[3] that the release rate of silica from a wide range of silicate glasses can be modeling using Equation 6-4:

$$RR = kA(1-C/K)$$

<div align="right">Equation 6-4</div>

where:

RR = release rate

A = amount of material (typically described in terms of area but mass was used in this work)

k = a constant dependent on pH and temperature

C = the concentration of the released species

K = the saturation limit of the released specie (a quasi-equilibrium constant)

This equation was used to model the release calcium and aluminum from the insulation materials as well as silicon. The steps used to develop the model follow:

1. Values of K and k were estimated for each run (e.g. K and k were estimated for the release of calcium from CalSil at 190°F and pH 4.1). A non-linear regression using Marquardt's algorithm was for estimation.

2. The various K and k values from different pHs and temperatures were all collected for the release of a given species from a material (e.g. The six k and six K values for Ca release from CalSil were considered together)

3. An equation was fit to each K and k value to model the temperature and pH variation of these parameters.

The form of each equation used to model the temperature and pH dependence of K is given in Equation 6-5:

$$K = 10^{[a + b(pHa) + c(1000/T)]}$$

<div align="right">Equation 6-5</div>

where:

a, b, and c are the fitted constants and T = temperature (°K)

likewise, Equation 6-6 was used to fit the rate constant k:

$$k = 10^{[d + e(pHa) + f(1000/T)]}$$

<div align="right">Equation 6-6</div>

Thus, six constants and three equations were used to predict the rate of release of a given species from a material as a function of pH, temperature and concentration of that species.

The modeling constants for different insulation materials are given in Table 6.2-3.

Table 6.2-3: Constants for Release Rate Prediction

Class	Released Material	Saturation Constant "K"			Rate Constant "k"		
		a	b	c	d	e	f
Calcium Silicate	Ca	-2.4063	-0.17595	1.967023	-2.35331	-0.15044	1.820687
Calcium Silicate	Si	0.12735	0.03197	0.71658	7.55470	-0.04084	-2.02198
Concrete	Ca	-0.15969	-0.04542	0.95477	5.31705	-0.07459	-1.10803
Concrete	Al	2.35338	0.06829	-0.70953	9.23778	0.05404	-3.34577
Concrete	Si	1.05597	0.01483	0.11862	3.50061	-0.01713	-0.74261
E-Glass	Ca	1.82949	0.06821	-0.47088	3.67611	0.02616	-0.96191
E-Glass	Si	5.20122	0.10404	-1.50553	7.46511	0.16247	-2.55813
E-Glass	Al	3.72351	0.14041	-1.69396	10.35371	0.17064	-4.17804
Min-K	Si	1.17043	0.10511	-0.07315	7.41106	0.17893	-1.93332
Aluminum Silicate	Al	5.52900	0.24010	-2.51326	8.48062	0.20749	-3.32039
Aluminum Silicate	Si	7.51336	0.18619	-2.89181	7.17588	0.11502	-2.42532
Mineral Wool	Ca	2.30159	0.12022	-0.82549	1.98549	0.09009	-0.52443
Mineral Wool	Al	8.96613	0.10871	-2.37200	6.62900	0.13222	-2.57256
Mineral Wool	Si	5.95046	0.06796	-1.43151	6.07665	0.16569	-2.17413
Interam	Si	13.60515	0.18354	-3.81145	15.69692	0.34838	-6.05941

The multiple R value is given in Table 6.2-4 for each of the linear regressions. The multiple R value is a measure of correlation with a value of "1" indicating a perfect prediction of k or K from the pH, T, and concentration data.

Table 6.2-4: Multiple R Values

Class	Released Material	Prediction of log(K)	Prediction of log(k)
Calcium Silicate	Ca	0.93	0.71
Calcium Silicate	Si	0.83	0.85
Concrete	Ca	0.78	0.94
Concrete	Al	0.43	0.37
Concrete	Si	0.52	0.50
E-Glass	Ca	0.66	0.95
E-Glass	Si	0.80	0.84
E-Glass	Al	0.67	0.88
Min-K	Si	0.91	0.89
Aluminum Silicate	Al	0.91	0.89
Aluminum Silicate	Si	0.98	0.83
Mineral Wool	Ca	0.99	0.60
Mineral Wool	Al	0.94	0.95
Mineral Wool	Si	0.88	0.99
Interam	Si	0.74	0.69

6.2.5 Model Verification

Aluminum and CalSil are anticipated to contribute heavily to precipitation in many plants so model predictions for releases from these materials were verified by comparing the predictions to those obtained experimentally in other laboratories or to predictions make by other verified software.

The chemical effects dissolution model was verified for aluminum dissolution by comparing the aluminum corrosion predictions to those obtained with the computer code GENNY[6]. The GENNY computer program calculates hydrogen produced from aluminum corrosion in a post-LOCA environment. The chemical effects aluminum release data can be converted to hydrogen release using Equation 6.7 below:

$$2Al + 3H_2O = Al_2O_3 + 3H_2$$

Equation 6.7

Post-LOCA aluminum corrosion was estimated for the time-temperature-pH evolution using GENNY and also with the chemical effects model. Good agreement was obtained. The chemical effects model predicted an average hydrogen generation rate of 36.1 standard cubic feet per minute over the first three hours of the accident, while GENNY predicted 39.3.

Table 6.2-5: Containment Temperature and Coolant pH Timelines used in Verification of Aluminum Release Rate Predictions

Start of Interval (hrs)	End of Interval (hrs)	Average Interval pH	Average T (°F)
0.0000	0.0001	10.5	140.0
0.0001	0.0003	10.5	160.0
0.0003	0.0006	10.5	180.0
0.0006	0.0008	10.5	202.5
0.0008	0.0017	10.5	222.5
0.0017	0.0028	10.5	240.0
0.0028	0.0056	10.5	257.5
0.0056	0.0278	10.5	270.0
0.0278	0.1111	10.5	272.5
0.1111	0.3472	10.5	267.5
0.3472	1.0000	10.5	247.5
1.0000	1.3889	10.5	182.5
1.3889	2.0000	10.0	142.5
2.0000	3.0000	9.5	148.5

The predictions for the dissolution of CalSil were verified by predicting calcium release in ANL CalSil dissolution tests[8] and comparing the predictions to the actual measured calcium levels. The results are shown in Table 6.2-6. The trend of increasing dissolution with decreasing pH was predicted by the model. The saturation of solutions was also predicted. However, the chemical effects model over-predicted the calcium concentrations for dissolution experiments performed at pH 4.5, 7, and 10.1 for all but one of the measurements. The chemical effects model under-predicted the rate of CalSil release for the pH 4 runs, but over-predicted the

apparent saturation level. The moderate over-prediction of saturation values occurred because data was taken at intervals that were too long to capture the rapid initial dissolution of CalSil.

Overall, the model performance for calcium silicate dissolution appears to be conservatively high but reasonable, especially given the variability in the experimental values.

Statistical estimation of the confidence interval for each parameter in Table 6.2-3 was performed. Typically, the confidence intervals were quite large ($\pm$ 100% of parameter value) due to the small numbers of samples used in the fitting process. More replicates are necessary to evaluate the model errors statistically.

Table 6.2-6: Prediction of Calcium Levels in Argonne CalSil Dissolution Tests

Test	Starting pH	T (C)	Time	CalSil Added (g/l)	Measured Ca (ppm)	Model Prediction (ppm)
1	4	60	35	6	176	48
2	4	60	35	15	256	114
3	4	60	35	25	244	181
4	4	60	35	166	228	588
5	4	60	240	6	196	307
6	4	60	240	15	195	521
7	4	60	240	25	195	600
8	4	60	240	166	168	624
9	4.5	60	240	6	156	256
10	4.5	60	240	15	169	430
11	4.5	60	240	25	184	492
12	4.5	60	240	166	127	509
13	7	62	240	2	45	40
14	7	62	240	6	88	95
15	7	62	240	25	69	167
16	7	62	1440	2	73	140
17	7	62	1440	6	108	170
18	7	62	1440	25	102	170
19	10.1	60	210	6	17	30
20	10.1	60	210	15	18	47
21	10.1	60	210	25	20	52
22	10.1	60	210	166	23	53

6.2.6   References

6.2-1   LA-UR-05-0124, Integrated Chemical Effects Test Project: Test #1 Data Report, June 2005.

6.2-2   V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

6.2-3   J. C. Griess and A. L. Bacarello, "Design considerations of Reactor Containment Spray Systems- Part III. The Corrosion of Materials in Spray Solutions," Oak Ridge National Laboratory Report ORNL-TM-2412, Part III.

6.2-4   M. J. Bell, J. E. Bulkowski, L. F. Picone, "Investigation of Chemical Additives for Reactor Containment Sprays" WCAP-7153A, April, 1975.

6.2-5   William L. Bourcier, "Critical Review of Glass Performance Modeling", Argonne National Laboratory Report ANL-94/17, July 1994.

6.2-6   James Sejvar, "Release of GENNY 5.2", SAE-REA-00-586, March 2000.

6.2-7   D. M. Chapman, "Surry 1 & 2 Mini-Uprate Post-LOCA Hydrogen Generation Analysis, CN-REA-02-47, June, 2002, Westinghouse Electric Company.

6.2-8   J. Oras, J. H. Park, K. Kasza, K. Nalesan, W. J. Shack, "Chemical Effects/Head Loss Testing Quick Look Report, Tests 1&2, September 16, 2005.

6.3   USE OF RELEASE RATE EQUATIONS TO DETERMINE RELEASES AND CONCENTRATIONS

The initial step in determination of release rates is to define the quantity of starting materials that will be exposed to the coolant. The amount of coolant in the ECCS should be determined using the average mass during the LOCA being modeled. The amount of each material in containment should be defined and assigned to the appropriate class per the class assignments in Section 3.2. The total quantity of material in each class should then be calculated.

The quantities of each material should be converted to the units used in this model. The units to be used are shown in Table 6.3-1 along with the units for release.

Table 6.3-1: Units for Chemical Model

Material	Material Units	Release Units
Aluminum	m^2	mg/m^2-min
Calcium Silicate	kg	mg/kg-min
Concrete	kg	mg/kg-min
E-glass	kg	mg/kg-min
Min-K	kg	mg/kg-min
Aluminum Silicate	kg	mg/kg-min
Mineral Wool	kg	mg/kg-min
Interam	kg	mg/kg-min

Density values are needed to convert insulation volume to mass and such density values should be material specific. For all materials other than concrete, the "as-fabricated" density values given in Table 3-2 of NEI 04-07 (Reference 6.3-1) or density values dictated by plant requirements should be used. Concrete is typically described in terms of uncoated surface area, and this should be converted to an equivalent number of kilograms of pulverized concrete using

the conversion factor of 1.0058E-5 kg/ft². This conversion factor is determined from the specific surface area for concrete given in Section 5.1.2.1 to be 9.24 m²/g.

Concrete conversion factor = (1 / 9.24 m²/g) / 10.76 ft²/m² / 1000 g/kg = 1.0058E-5 kg/ft²

The next step is development of a temperature and pH profile for the loss of coolant transient. These data will be used as inputs in a numeric integration of the release rate equations to determine the release of a species over time as well as the dissolved concentration of the species over time. A separate pH and temperature profile should be used for the spray.

The next step is the numerical integration of the release over a suitable interval. The integration interval should be short enough to capture information on rapidly changing temperatures and pH values. Typically, the integration period should be near one minute early in the LOCA. For each time interval and each species, use the containment material class mass, the interval pH and the interval temperature to predict the release rate using Equations 6-2 and 6-4 through 6-6. The concentration of each species at the start of the interval in units of ppm is also required for the prediction. Assume that the concentration is zero for all species at time zero, the start of the LOCA. The release rate is multiplied times the interval length to calculate the mass release. The mass release in mg is added to the integral mass, and the total mass is divided by the coolant mass in kg to get the new species concentration. The total mass released into the coolant should be limited by the initial mass if this quantity is known.

6.3.1 Reference

6.3-1   NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

6.4   DETERMINATION OF THE QUANTITY OF PRECIPITATES GENERATED

Due to the limited solubility of the key chemical precipitates, it may be conservatively assumed that essentially all of the dissolved aluminum will form precipitates upon cooling. Because the solubility of calcium silicate increases at lower temperatures (constant pH conditions) dissolved calcium will remain in solution in the absence of phosphate. Thus, the types of precipitates generated will be dependant on plant sump chemistry as well as sump materials.

Based on the chemistry of the key precipitates formed from predominant dissolved species, it is judged that the quantity and morphology of the precipitates would not be fundamentally affected by changes in temperature (predominantly cooling) during precipitate formation. Specifically, the precipitates generated are amorphous and demonstrate qualitatively slow settling behavior and qualitatively poor filterability. It is not expected that temperature changes would fundamentally alter these characteristics with respect to their effect on sump screen performance. Additionally, based on the very low solubility of the key precipitates, the model assumes that 100 percent of the aluminum and calcium (in the presence of phosphate) form precipitates. This conservative assumption effectively eliminates any influence temperature variations during precipitate formation may have on the ultimate quantity of precipitates formed.

To determine the quantity of the key precipitates, the quantity of the elements that make up the precipitates must be determined using the chemical model. It is assumed that sodium (Na), hydroxyl (OH⁻), and phosphate (if applicable) will be present in excess. Using the stoichiometry of the precipitates, the quantities may be calculated directly. The formulas for the three key precipitates are provided below. Note, for the case of sodium aluminum silicate, it is first necessary to determine whether aluminum or silicon is the limiting component. An example of generation of the calcium phosphate formula is also provided below.

Plants Using Either Sodium Hydroxide or Sodium Tetraborate Buffers

Based on thermodynamic calculations previously reported[1], dissolved aluminum, sodium and silicate will precipitate as sodium aluminum silicate ($NaAlSi_3O_8$). It is expected that the quantity of sodium aluminum silicate generated will be limited by the amount of available silicate. This will be the case if the concentration of silicate is less than 3.11 times the concentration of aluminum. All aluminum that does not precipitate as sodium aluminum silicate will precipitate as aluminum oxyhydroxide (AlOOH).

Thus, the quantity of precipitate generated may be calculated as:

If [Si] > 3.12*[Al] : $NaAlSi_3O_8$ = [Si] * 3.11

If [Si] < 3.12*[Al] : $NaAlSi_3O_8$ = [Al] * 9.72

AlOOH = {[Al] – 0.32 * [Si] } * 2.22

Plants using Trisodium Phosphate Buffer

For plants using trisodium phosphate, calcium phosphate with an assumed chemical form of $Ca_3(PO_4)_2$ will also be generated in addition to sodium aluminum silicate and aluminum oxyhydroxide as discussed above. Note, the presence of silicate would be expected to inhibit the release of aluminum due to corrosion of metallic aluminum; however, this factor is not considered in this model. The quantity of calcium phosphate generated may be calculated as:

$Ca_3(PO_4)_2$ molecular weight: 310.18 g-atom/mole

Ca molecular weight: 40.08 g-atom/mole

Ca to $Ca_3(PO_4)_2$ conversion factor: $Ca_3(PO_4)_2$ molecular weight/3*Ca molecular weight

where the factor of three accounts for the fact that there are three calcium atoms per atom of calcium phosphate.

$Ca_3(PO_4)_2$ = [Ca] * 2.58

6.4.1 Reference

6.4-1 V. Jain, X. He, Y.-M. Pan "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191, NUREG/CR-6873, April 2005.

6.5 SENSITIVITY STUDY

6.5.1 Base Case

The performance of the model was investigated using the spreadsheet implementation described in Section 8.2 along with containment data from the GSI-191 Containment Materials Survey. The model was first used to predict the precipitate formation at a CalSil plant with the input parameters set at levels expected from a large break LOCA. After the "base run" some of the key inputs were then varied and changes in the predicted precipitation were recorded and evaluated.

The containment materials in the base run are given in Table 6.5-1. The plant that was simulated had a fairly simple mix of materials as was not unusual for a CalSil plant. The aluminum area was near the center of the range of survey responses and, as was typical from the plant surveys, most of the aluminum was not submerged. The exact mass of aluminum was not known for this plant, so a conservative large number (1,000,000 lbm) was entered for both the mass of submerged and un-submerged aluminum. The break analysis predicted that 97 cubic feet of CalSil would be dislodged and transported into the sump. The fiberglass transported to the sump was 1180 cubic feet, a value toward the center of the fibrous insulation distribution among the surveyed plants. While the containment had a large area of exposed concrete, none was predicted to be submerged or transported to the sump.

Table 6.5-1: Materials Input for Chemical Model

Class	Material	Amount
Coolant	Sump Pool Volume (ft3)	55,169
Metallic Aluminum	Aluminum Submerged (sq ft)	1575
	Aluminum Submerged (lbm)	1000000
	Aluminum Not-Submerged (sq ft)	155925
	Aluminum Not-Submerged (lbm)	1000000
Calcium Silicate	CalSil Insulation(ft3)	97
	Asbestos Insulation (ft3)	0
	Kaylo Insulation (ft3)	
	Unibestos Insulation (ft3)	
E-glass	Fiberglass Insulation (ft3)	1180
	NUKON (ft3)	
	Temp-Mat (ft3)	
	Thermal Wrap (ft3)	
Silica Powder	Microtherm (ft3)	0
	Min-K (ft3)	0
Mineral Wool	Min-Wool (ft3)	0
	Rock Wool (ft3)	
Aluminum Silicate	Cerablanket (ft3)	
	FiberFrax Durablanket (ft3)	0
	Kaowool (ft3)	
	Mat-Ceramic (ft3)	
	Mineral Fiber (ft3)	
	PAROC Mineral Wool (ft3)	
Concrete	Concrete (ft2)	0
Trisodium Phosphate	Trisodium Phosphate?	1
Interam	Interam (ft3)	0

The default density values used for the containment materials are collected in Table 6.5-2.

Table 6.5-2: Density Values Used in Model and Calculated Masses

Class	Material	Amount	Density (lb/ft3)	Mass(kg)
Coolant	Sump Pool Volume (ft3)	55169	60.957	1525418.1
Metallic Aluminum	Aluminum Submerged (sq ft)	1575.00		0.0
	Aluminum Submerged (lbm)	1000000		45359.7
	Aluminum Not-Submerged (sq ft)	155925		0.0
	Aluminum Not-Submerged (lbm)	1000000		45359.7
Calcium Silicate	CalSil Insulation(ft3)	97	14.15	622.6
E-glass	Fiberglass Insulation (ft3)	1180	4	2141.0

The pH and temperature timelines are shown in Table 6.5-3. Only the sump pH values were provided by the plant. The spray pH values were at first assumed to be at the pH of the RWST, and then after the start of recirculation, the pH of the spray was assumed to be the same as the sump. The temperatures of the sump and containment atmosphere were not provided by the plant

but instead were engineering estimates selected for the purpose of this exercise. It was assumed that recirculation started after 30 minutes.

Table 6.5-3: Variation of pH and Temperature with Time after LOCA-Base Case

Time (sec)	(min)	(hr)	(day)s	Sump pH	Sump Temp. (°F)	Sump Mixed 1=Yes	Spray pH	Containment Temp. (°F)
6	0	0	0	5.6	212	0	4.4	222
30	1	0	0	5.6	222	0	4.4	232
60	1	0	0	5.6	212	0	4.4	222
120	2	0	0	5.6	213	0	4.4	223
180	3	0	0	5.6	214	0	4.4	224
200	3	0	0	5.6	214	0	4.4	224
400	7	0	0	6.7	220	0	4.4	230
600	10	0	0	7.2	224	0	4.4	234
800	13	0	0	7.4	229	0	4.4	239
1000	17	0	0	7.5	230	0	4.4	240
1200	20	0	0	7.5	230	0	4.4	240
1400	23	0	0	7.5	222	0	4.4	232
1600	27	0	0	7.5	211	0	4.4	221
1800	30	1	0	7.5	200	0	4.4	210
3200	53	1	0	7.5	187	0	7.5	197
4600	77	1	0	7.5	200	0	7.5	210
6000	100	2	0	7.5	201	0	7.5	211
7400	123	2	0	7.5	201	0	7.5	211
8800	147	2	0	7.5	201	0	7.5	211
10200	170	3	0	7.5	200	0	7.5	210
11600	193	3	0	7.5	197	0	7.5	207
13000	217	4	0	7.5	194	0	7.5	204
14400	240	4	0	7.5	192	0	7.5	202
46400	773	13	1	7.5	162	0		
86400	1440	24	1	7.5	140	0		
172800	2880	48	2	7.5	140	0		
259200	4320	72	3	7.5	140	0		
345600	5760	96	4	7.5	140	0		
432000	7200	120	5	7.5	140	0		
864000	14400	240	10	7.5	140	0		
1296000	21600	360	15	7.5	140	0		
1728000	28800	480	20	7.5	140	0		
2160000	36000	600	25	7.5	140	0		
2592000	43200	720	30	7.5	140	0		

The model predictions for the base case are listed in Table 6.5-4. After 30 days, a total of 619 kg of $NaAlSi_3O_8$ was precipitated along with 51.2 kg of $AlOOH$ and 595.3 kg of $Ca_3(PO4)_2$. The elemental releases leading to these precipitates have been plotted in Figure 6.5-1. The

contribution of each containment material to each elemental release has also been indicated in the figure. Overall, submerged aluminum was responsible for 2.4% of the total mass release, while un-submerged aluminum contributed 14.2 percent. CalSil and E-glass contributed 70.6% and 12.8%, respectively.

The contribution of each containment material to each of the precipitates is also plotted in Figure 6.5-2. The submerged aluminum was the source of 4.1% of the precipitate mass and un-submerged aluminum added 24.1% of the total. CalSil was the largest contributor at 62.2%, and the E-glass added only 9.6% of the total precipitate mass.

Table 6.5-4: Elemental Releases and Precipitation for Base Case

End of Interval (hrs)	Average Interval pH	Average Temp (ºF)	Ca Release (kg)	Si Release (kg)	Al Release (kg)	$NaAlSi_3O_8$ Precipitate (kg)	AlOOH Precipitate (kg)	$Ca_3(PO_4)_2$ Precipitate (kg)
0.01	5.6	217	0.03	0.05	0.13	0.2	0.3	0.07
0.02	5.6	217	0.06	0.12	0.30	0.4	0.6	0.16
0.03	5.6	212.5	0.13	0.24	0.59	0.8	1.1	0.33
0.05	5.6	213.5	0.19	0.37	0.89	1.1	1.7	0.50
0.06	5.6	214	0.22	0.41	0.99	1.3	1.9	0.56
0.11	6.15	217	0.43	0.91	2.12	2.8	4.1	1.10
0.17	6.95	222	0.63	1.58	3.46	4.9	6.6	1.62
0.22	7.3	226.5	0.82	2.38	5.03	7.4	9.5	2.13
0.28	7.45	229.5	1.02	3.27	6.76	10.2	12.7	2.64
0.33	7.5	230	1.22	4.18	8.52	13.0	15.9	3.14
0.39	7.5	226	1.41	5.01	10.06	15.6	18.8	3.64
0.44	7.5	216.5	1.60	5.68	11.19	17.7	20.8	4.12
0.50	7.5	205.5	1.78	6.20	11.95	19.3	22.1	4.59
0.89	7.5	193.5	3.04	8.94	15.64	27.8	28.4	7.85
1.28	7.5	193.5	4.27	11.64	22.01	36.2	40.6	11.00
1.67	7.5	200.5	5.44	14.78	29.98	46.0	56.1	14.04
2.06	7.5	201	6.58	17.91	38.07	55.7	71.8	16.97
2.44	7.5	201	7.67	20.98	46.16	65.3	87.6	19.80
2.83	7.5	200.5	8.73	23.96	54.11	74.5	103.1	22.53
3.22	7.5	198.5	9.76	26.75	61.58	83.2	117.7	25.18
3.61	7.5	195.5	10.76	29.29	68.37	91.1	131.0	27.76
4.00	7.5	193	11.74	31.63	74.62	98.4	143.2	30.28
12.89	7.5	177	35.20	65.61	75.58	204.1	121.2	90.83
24.0	7.5	151	63.65	75.93	75.85	236.2	114.4	164.21
48.0	7.5	140	132.05	88.75	76.23	276.0	106.2	340.69
72.0	7.5	140	174.79	101.22	76.60	314.8	98.2	450.96
96.0	7.5	140	201.50	113.36	76.98	352.5	90.4	519.86
120.0	7.5	140	218.18	125.16	77.35	389.3	82.8	562.91
240.0	7.5	140	230.73	182.62	79.23	567.9	46.2	595.29
360.0	7.5	140	230.73	199.03	81.11	619.0	38.7	595.29
480.0	7.5	140	230.73	199.03	82.99	619.0	42.8	595.29
600.0	7.5	140	230.73	199.03	84.87	619.0	47.0	595.29
720.0	7.5	140	230.73	199.03	86.75	619.0	51.2	595.29
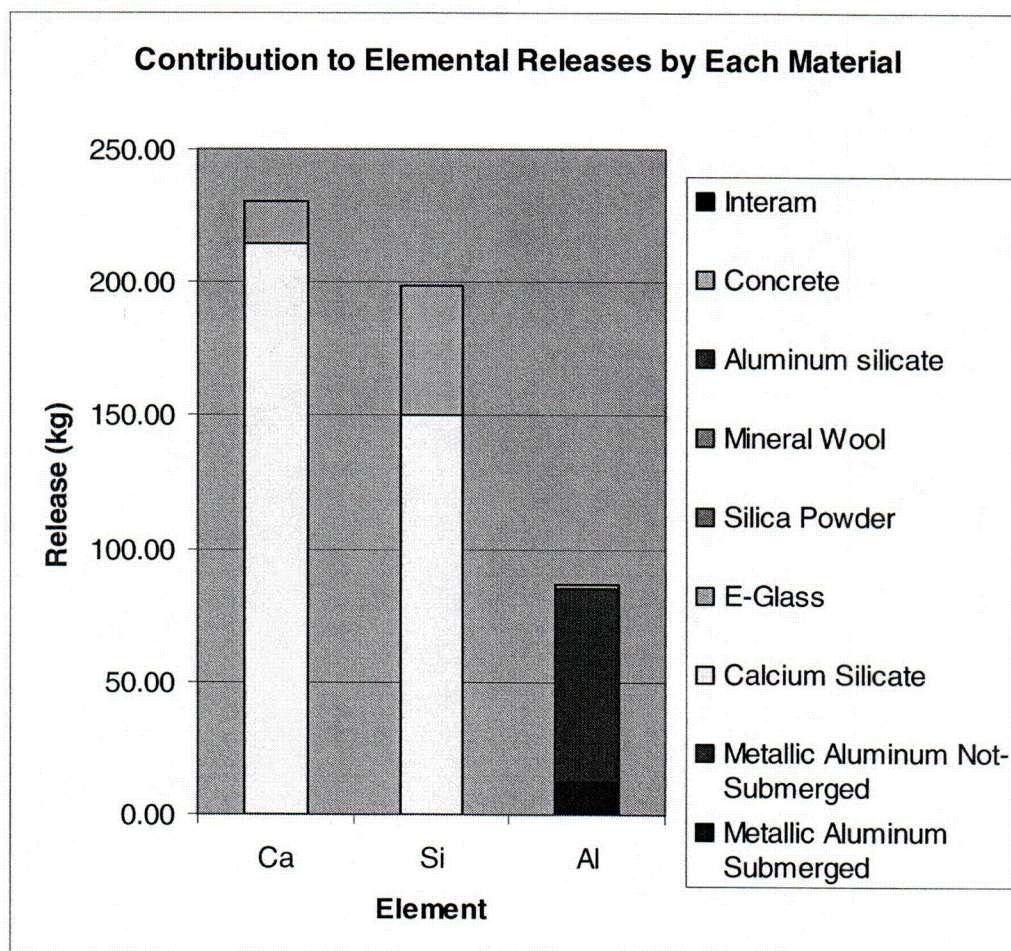
Figure 6.5-1: Predicted Elemental Releases by Source Material (Base Case)
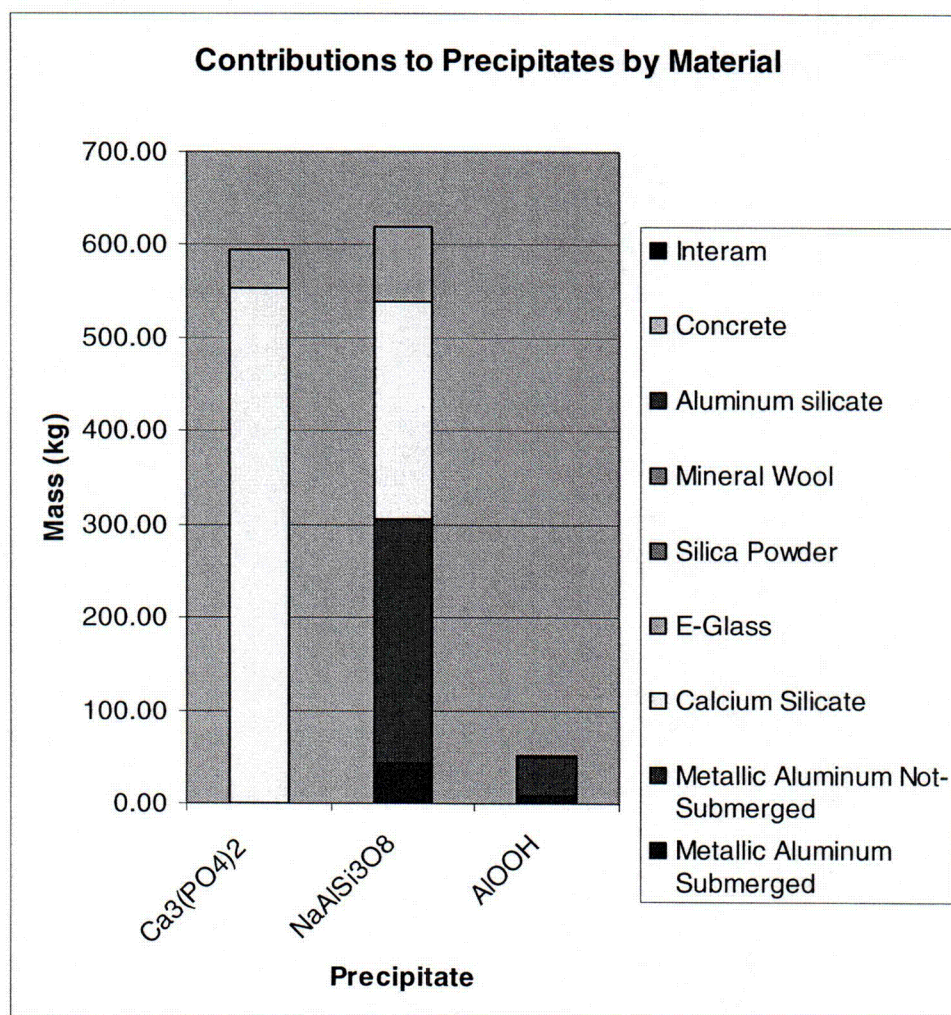
Figure 6.5-2: Predicted Precipitation by Source Material (Base Case)

Most of the aluminum was released during the spray phase of the LOCA when temperatures were high and a large area of aluminum was exposed to the spray solution. This is shown in Figure 6.5-3.
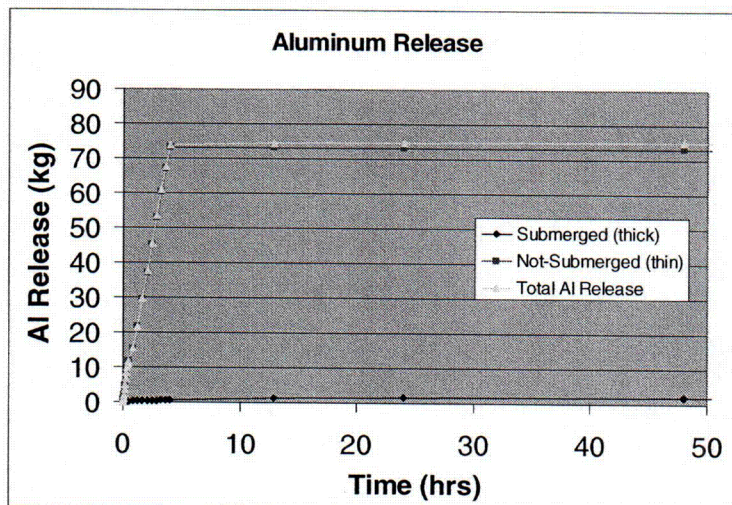
Aluminum Release

Figure 6.5-3: Predicted Release of Aluminum with Time (base case)

Most of the CalSil dissolution also took place shortly after the LOCA. In fact, the model indicated that by 120 hours, 94 percent of the CalSil that was transported to the sump had dissolved and that by 240 hours, all CalSil was in solution. The release of calcium from CalSil showing the rapid early release is shown in Figure 6.5-4.

Integral Ca Released from CalSil (base case)
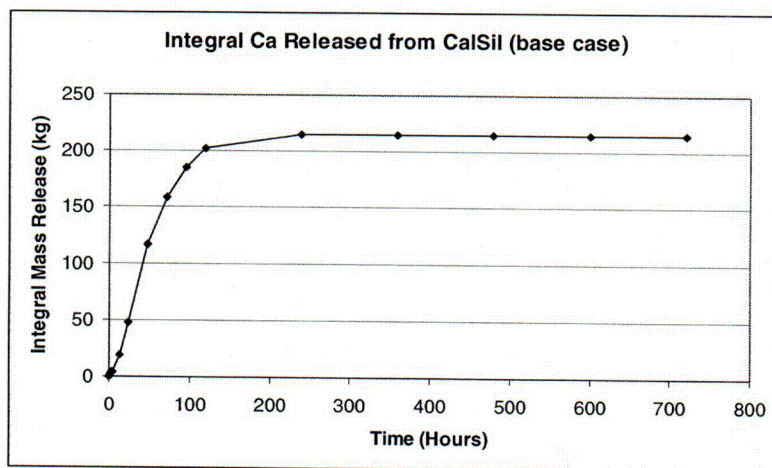
Figure 6.5-4: CalSil Release with Time Showing Complete Dissolution (base case)

The complete dissolution of CalSil predicted by the chemical effects model is consistent with the latest dissolution tests conducted at Argonne National Laboratory. These tests discovered that when CalSil was added to simulated coolant at 60°C (140°F) to a concentration of either 0.5 or 1.5 g/l, complete dissolution took place in about 100 hours. This was true, even when TSP was added to the simulated coolant at three separate rates (Reference 6.5-1).

6.5.2 Sensitivity to pH Change

The effect of pH change on precipitate mass was explored using the chemical effects model. Such a pH change could be accomplished in practice by adding or removing TSP mass from the containment baskets. In the model, the pH vs. time curves were modified by changing the maximum pH while keeping the minimum pH constant at a value of 5.6. Intermediate pH values were kept at the same relative location between the maximum and the minimum as in the base case. The maximum pH was varied between 5.6 and 10.5. The results are shown in Figure 6.5-5.

Effect of pH on Total Precipitate
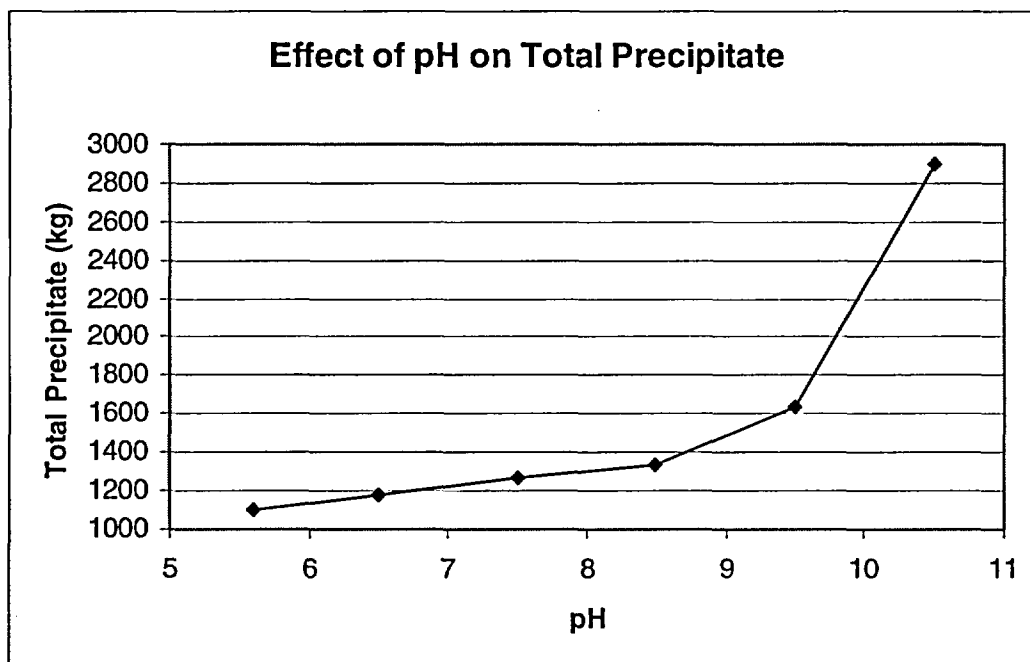
Figure 6.5-5: Effect of pH Variation on Total Precipitate Mass

The amount of precipitate generated increased slowly between pH values of 5.6 and 8.5. The precipitate mass total increased more rapidly between a pH of 8.5 and 10.5. The corrosion of aluminum during the spray phase was the main contributor to precipitate increase at high pH values. The CalSil dissolves completely during the 30 day post-LOCA period at pH values between 5.6 and 8.5. At pH values above pH 8.5, the CalSil dissolution decreases, but this benefit is opposed by the steep increase in aluminum corrosion.

6.5.3 Sensitivity to Temperature Change

The effect of changing temperature was explored in a manner similar to the pH sensitivity determination just described. The minimum temperature of 140°F was fixed and the maximum temperature was varied up to a value of 270°F. Intermediate temperature values were kept at the same relative location between the maximum and minimum as in the base case.

The results of the temperature sensitivity study are shown in Figure 6.5-6. Increasing the maximum containment temperature increased the amount of precipitate generated. The total percentage change was relatively small at about 20 percent. The effect was due mainly to the increase of aluminum corrosion with temperature. The CalSil completely dissolved at all temperatures before the 30 day recirculation time was complete.
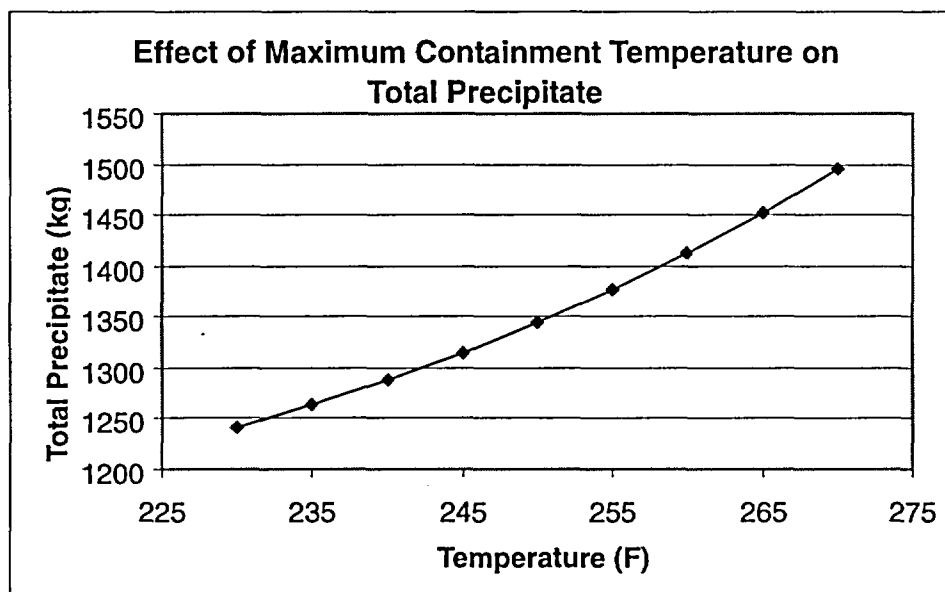
Figure 6.5-6: Effect of Temperature Variation on Total Precipitate Mass

6.5.4 Sensitivity to Buffering Agent

A change in buffer type from TSP to Borax was simulated by taking the TSP out of the materials list in the chemical effects model. The pH and temperature profiles were maintained at the base case levels. About half of the precipitation was observed with Borax compared to TSP as shown in Figure 6.5-7. Removing the TSP did not completely eliminate precipitation because of the significant aluminum corrosion. The aluminum reacted with the silica released from the CalSil to form sodium aluminum silicate. The relative amounts of sodium aluminum silicate and aluminum oxide hydroxide are shown in Figure 6.5-8.

Effect of Buffer Type
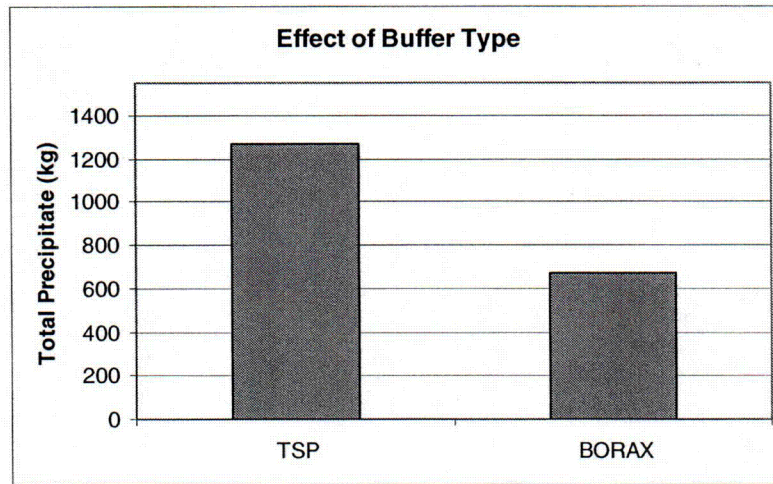
Figure 6.5-7: Effect of Changing Buffer on Total Precipitate Mass

Contributions to Precipitates by Material
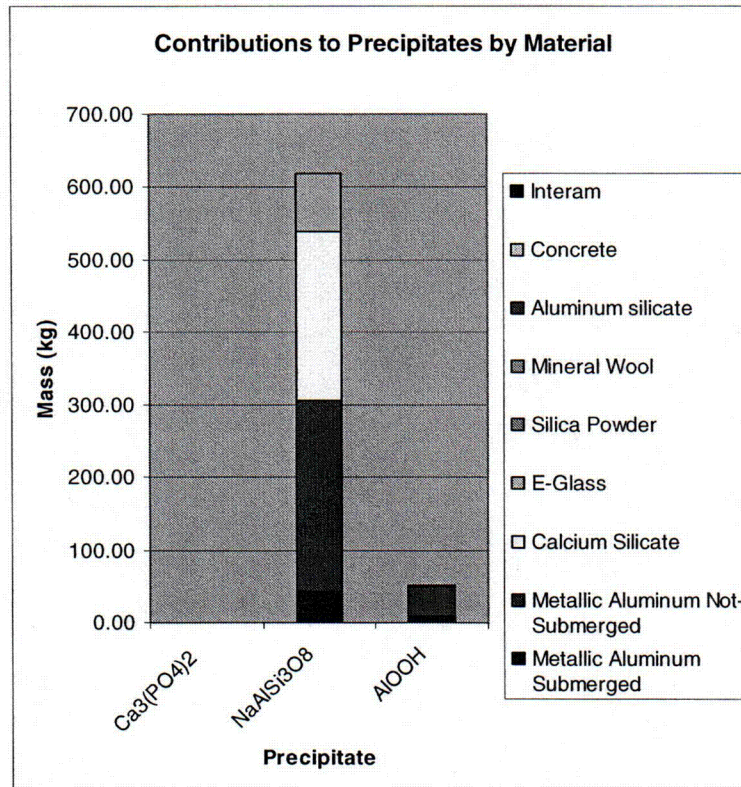
Figure 6.5-8: Effect of Changing Buffer on Precipitate Formation

6.5.5 Sensitivity to Exposed Concrete Surface Area

The containment survey that was used as the basis for the sensitivity study did not list any exposed and submerged concrete area, but since most plants have this source, the model was run with varying amounts of concrete exposed. The results are shown in Figure 6.5-9.

Effect of Exposed Concrete on Total Precipitate Mass Formed
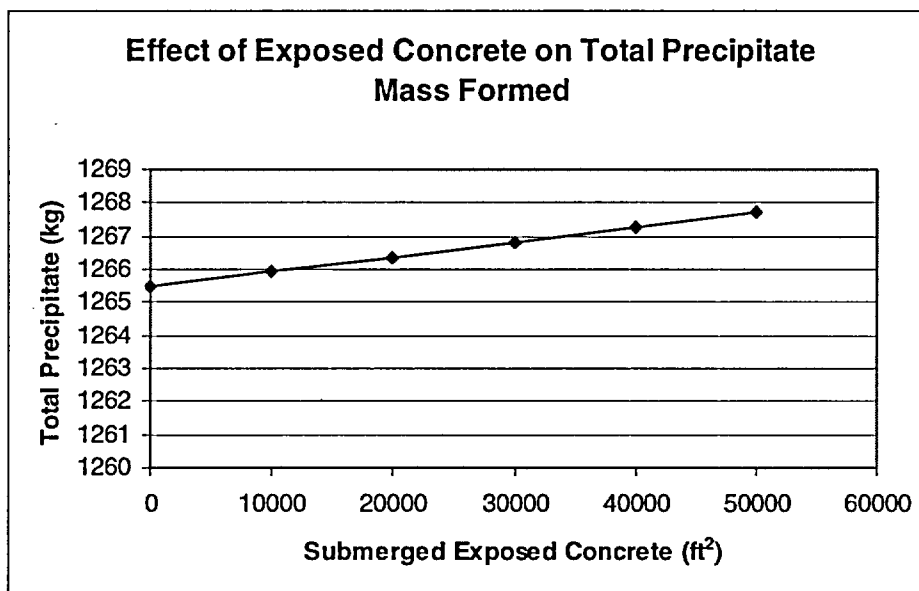
Figure 6.5-9: Effect of Adding Exposed Concrete to Base Case Materials

The precipitation of materials from concrete dissolution appears to be negligible even when high exposed surface areas are input.

6.5.6 Reference

6.5-1 J. Oras, J. H. Park, K. Kasza, K. Natesan, W. J. Shack, Chemical Effects/Head-Loss Testing, Quick Look Report, Tests ICET-3-4 to 11, January 20, 2006.

7.0 PARTICULATE GENERATOR

7.1 PURPOSE

The purpose of the particulate generator is to create prototypical solid chemical products (precipitates) for sump screen performance testing at vendor test facilities. After generation in the unit, the chemical products may be treated as another class of inert debris for strainer testing purposes. The system generally comprises one or more chemical reaction tanks, one or more precipitate transfer pumps, a precipitate mix holding tank, and interconnecting hoses/piping and valves. The system is intended to be operated using normal potable water at ambient temperature, although operation at elevated temperature may be conducted if desired.

The filtration and settling behaviors of the key precipitates are influenced by the amorphous and hydration properties of the materials. These properties are based on the chemical nature of the specific precipitates and are due to the fact that the species are formed *in situ*[1]. These exact behaviors may not result if crystalline, non-hydrated solid starting materials are used to simulate the precipitates (for example, use of solid calcium phosphate). Also, other solid starting materials may not provide the same filtration, agglomeration and settling characteristics (for example, use of aluminum sulfate or alum in place of aluminum hydroxide). Therefore, if crystalline, non-hydrated, or other manufactured solid starting materials are to be used in sump screen testing, it is suggested that testing be performed to demonstrate the acceptability of the starting materials for simulating the amorphous and hydrated materials generated in the bench testing. If no testing of the filtration and settling characteristics of these materials is planned, it is recommended that the particulates be generated as described below to ensure materials with prototypical behaviors are used in screen testing. However, if vendors prefer to use manufactured materials in screen testing, the settling and filtration characteristics of these materials may be compared to the acceptance criteria presented in Section 7.8.

7.1.1 Reference

7.1-1 Giulietti, M., et al., "Industrial Crystalization and Precipitation from Solutions State of the Technique," Braz. J. Chem. Eng., Vol. 18(4), December 2001.

7.2 FUNCTIONAL REQUIREMENTS

7.2.1 General

The detailed design of the particulate generator is dependent on the size of the screen test facility and the plant-specific precipitate mix to be tested. For a given screen test facility, the expected variations in design would generally be limited to the number of chemical mixing tanks and transfer pumps required. Therefore, a generator constructed for a plant-specific test can be readily modified as required for use in additional plant-specific test programs.

All wetted materials used to construct the system must be chemically resistant to short-term exposure to the reactant chemicals used to prepare the precipitates, as well as long-term exposure

to oxygenated water. Suitable materials include austenitic stainless steel, high density polyethylene (HDPE), polytetrafluoroethylene (PTFE, e.g., Teflon), polypropylene, polyvinylchloride (PVC), Norprene, ethylene-propylenediene monomer (EPDM; for hose lining) and vinyl. Wetted components constructed of carbon/low alloy steel, zinc, aluminum or brass should not be used. The system is intended to be operated using normal potable water at ambient temperature, although operation at elevated temperature may be conducted if desired. Construction materials should be selected consistent with the desired test temperature range.

7.2.2   Equipment Details

Chemical Mixing and Holding Tanks

Chemical mixing tank(s) should be sized to contain at least 20 percent of the screen test system volume. Alternatively, smaller tanks may be used and particulates may be generated in several batches. The holding tank should be sized to hold the combined contents of the mixing tank(s). The tanks should be fitted with removable lids or have lidded openings for chemical additions and tank cleaning. Cone bottom tanks are recommended to facilitate complete precipitate transfer. The tank should be fitted with a mixer sized sufficiently to create a vortex in the tank. Air or electrically powered mixers may be used.

Transfer Pumps

The pump used to transfer the precipitates from the chemical reaction and holding tank(s) should be sized to transfer the tank contents in 20 minutes or less. Although the type of pump is not critical, peristaltic or diaphragm pumps are preferred to facilitate transfer of solid material and post-use clean out. Air or electrically powered pumps may be used.

Interconnections, Valves and Fittings

It is recommended that hose/flexible tubing be used to facilitate reconfiguring the system for plant-specific testing. To facilitate transfer of precipitate slurries and system clean out, ball valves should be used. The system should be constructed to minimize crevices and dead legs/low flow areas to facilitate system clean out.

Cleaning

After each use, the particulate generator should be rinsed with water and visually inspected to verify all particulates have been rinsed from the components. Special attention should be paid to valves, pumps and other areas where particulates may be trapped.

Waste Disposal

All precipitates and liquids should be disposed of in accordance with applicable federal, state and local laws. Typically, the waste can be sent directly to the sanitary sewer system with no pretreatment. However, the acceptability of this path must be determined locally.

7.3 GENERATION OF CHEMICAL PRECIPITATES

7.3.1 General

To prepare the precipitates, add ambient temperature water to the reaction tank and initiate stirring. Slowly add the reactants individually in the specified order, and allow them to dissolve completely before adding additional reactants. Chemical reactants may optionally be pre-dissolved in water prior to addition to the reaction tank. After reactant addition, maintain mixing for a minimum of one hour to allow chemical reactions to go to completion. Obtain a representative sample of the precipitate slurry for testing. Dilute the sample as directed below. Measure the pH, time to settle, and 1-hour wet volume of the precipitate. Time to settle is the time required to achieve less than 5 percent change in volume over a 30-minute period. The pH should be greater than 6.5 to verify complete reaction of the acidic metal salts. After the precipitates are determined to be acceptable, they may be injected directly into the screen test system.

Hardness minerals (e.g., calcium, magnesium, etc.) will not inhibit precipitate formation, nor affect the physical characteristics of the precipitates. However, these minerals may co-precipitate with the intentionally added metals (aluminum or calcium). Based on the low concentration of hardness minerals relative to the concentration of intentionally added metals, the contribution to the total quantity of precipitates generated would be negligible.

7.3.2 Precipitate Formation

<u>Aluminum Oxyhydroxide</u>

For each 100 grams of aluminum oxyhydroxide precipitate, add 625 grams of aluminum nitrate $(Al(NO_3)_3 \cdot 9H_2O)$. After the aluminum salt has dissolved, add 200 grams of sodium hydroxide (NaOH). Obtain a sample and dilute as required to obtain a precipitate concentration of 2.1 to 2.3 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 4.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of aluminum oxyhydroxide in a single mixing tank should not exceed 11 grams per liter.

<u>Calcium Phosphate</u>

For each 100 grams of calcium phosphate precipitate, add 170 grams of calcium acetate. After the calcium salt has dissolved, add 245 grams of trisodium phosphate (TSP). Obtain a sample and dilute as required to obtain a precipitate concentration of 0.9 to 1.1 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 4.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of calcium phosphate in a single mixing tank should not exceed 5 grams per liter.

Sodium Aluminum Silicate

The settling rate and filtration characteristics of sodium aluminum silicate are sufficiently similar to aluminum oxyhydroxide that aluminum oxyhydroxide may be used in lieu of sodium aluminum silicate. This approach simplifies precipitate generation and avoids use of sodium silicate, which may be considered hazardous. In the event it is necessary to form sodium aluminum silicate, the instructions are provided below.

For each 100 grams of sodium aluminum silicate precipitate, add 143 grams of aluminum nitrate $(Al(NO_3)_3 \cdot 9H_2O)$. After the aluminum salt has dissolved, slowly add 520 milliliters of sodium silicate solution (40% Na_4SiO_4). Obtain a sample and dilute as required to obtain a precipitate concentration of 9.6 to 9.8 grams per liter. After one hour, the resultant precipitate should have a minimum settling volume of 4.0 milliliters for a 10 ml sample.

To achieve prototypical settling behavior, the concentration of sodium aluminum silicate in a single mixing tank should not exceed 11 grams per liter.

7.4   PROOF-OF-PRINCIPLE APPARATUS

A pilot scale particle generator was constructed and tested to verify proper operation of the conceptual unit. A photograph of the assembled system is provided in Figure 7.4-1 and a diagram is provided as Figure 7.4-2. The laboratory system was constructed using the following components:

- Three 5-gallon capacity open topped, conical bottom HDPE tanks. Two tanks were used as chemical mixing tanks, and the third tank was used as the holding tank. Each tank was fitted with a HDPE lid and was mounted on an enamel coated steel stand. The chemical mixing tanks were fitted with a ½-inch polypropylene faucet in the side to facilitate decanting.

- One stand mounted, variable speed, 10,000 rpm electric mixer for each tank. The mixers operated on 115 VAC/60 Hz power, and were fitted with 12-inch stainless steel shafts with 1-3/8-inch stainless steel propellers.

- One electrically powered peristaltic pump to transfer the contents of each tank. The pumps had a maximum flow rate of 2.2 gpm, and operated on 115 VAC/60Hz power. The wetted parts were constructed of PVC and Norprene.

- One 5-gallon capacity cylindrical, flat bottom, open top HDPE tank that served as the receiver tank to represent the strainer test system.

- The tanks/pumps were connected using 1/2-inch inner diameter, smooth bore nylon tubing.

All system components were procured as standard commercial items from McMaster-Carr.
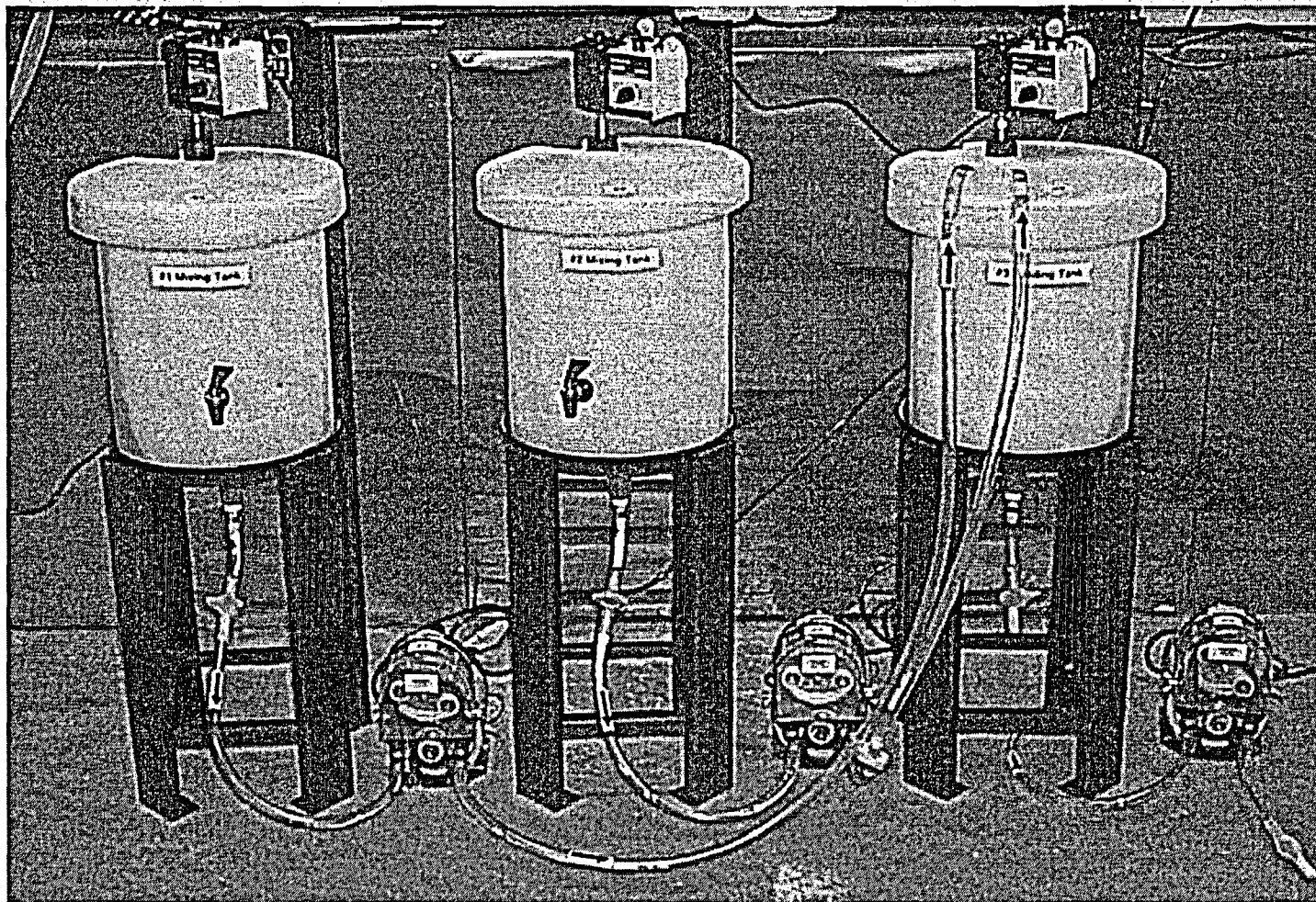
Figure 7.4-1: Photograph of Assembled Pilot Scale Particulate Generator

Figure 7.4-2: Block Diagram of Particulate Generator

Precipitate Transfer Pumps

Transfer Pump

Chemical Mixing Tanks

Holding Tank

Receiver Tank
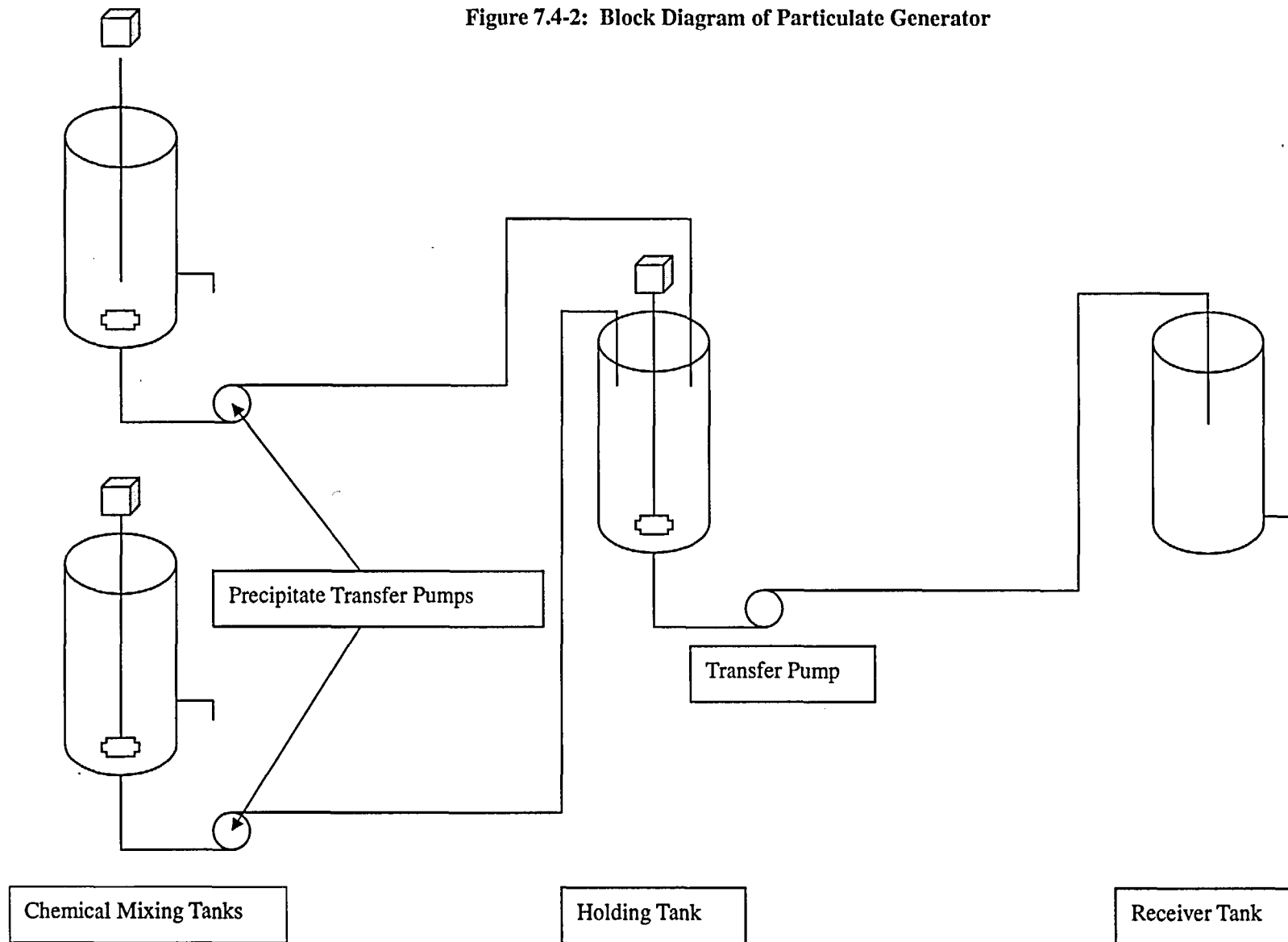
7.5 PARTICULATE GENERATOR QUALIFICATION TESTING

Testing was performed to verify expected operation of the particulate generator. Calcium phosphate particulate was generated to achieve a final particulate concentration of 1.0 grams per liter in a simulated strainer test loop. Aluminum oxyhydroxide was generated to achieve a final particulate concentration of 2.2 grams per liter in a simulated test loop. Due to the similarity of the physical characteristics and preparation techniques of sodium aluminum silicate with those of aluminum oxyhydroxide, qualification testing of sodium aluminum silicate in the particulate generator was not considered necessary. The particulates were generated in accordance with the guidance provided in the preceding section. All testing was performed using potable water (Churchill, PA) with a temperature of about 55°F.

7.5.1 Calcium Phosphate

To prepare the particulate, the chemical mixing tank was filled with two gallons of water. Mixing was initiated, and 64.5 grams of calcium acetate monohydrate was slowly added, followed by addition of 92.8 grams of trisodium phosphate dodecahydrate. These addition quantities were selected to obtain a total of 38 grams of calcium phosphate in order to achieve a diluted concentration of 1.0 grams per liter in a simulated 10-gallon test system volume.

The solution was mixed for 60 minutes, and then mixing was secured. The solution was sampled and analyzed for pH. The pH of the potable water was also measured for reference. The results of these analyses are provided in Table 7.5-1.

A one gallon aliquot of the holding tank contents was transferred to a tank containing 5 gallons of water to simulate transfer of the particulate into a test loop. The resultant diluted precipitate was sampled and analyzed for pH, time to settle, settling volume and filterability. The settling and filtration characteristics were consistent with those observed during bench-scale testing of the precipitates generated from addition of phosphate to solutions containing calcium from dissolution of CalSil and concrete.

Table 7.5-1: Analysis Results for Samples Obtained during Calcium Phosphate Generation Test

Sample Description	pH	Conductivity (μS/sm)	2-hr Settled Volume (ml)
Potable Water	8.02	254	NA
Mixing Tank	9.05	NM*	NM*
Diluted	8.69	NM*	5.6

*NM = Not measured

7.5.2 Aluminum Oxyhydroxide

To prepare the particulate, the chemical mixing tank was filled with two gallons of water. Mixing was initiated, and 526 grams of aluminum nitrate nonahydrate was slowly added, followed by addition of 168 grams of sodium hydroxide. These addition quantities were selected to obtain a total of 84 grams of aluminum oxyhydroxide to achieve a diluted concentration of 2.2 grams per liter in a simulated 10-gallon test system volume.

The solution was mixed for 60 minutes, and then mixing was secured. A sample was obtained and analyzed for pH. A one gallon aliquot of the holding tank contents was transferred to a tank containing five gallons of water to simulate transfer of the particulate into a test loop. The resultant diluted precipitate was sampled and analyzed for pH, time to settle, settling volume and filterability. The settling and filtration characteristics were consistent with those observed during bench-scale testing of the precipitates generated from corrosion of aluminum metal.

Table 7.5-2: Analysis Results for Samples Obtained during AlOOH Generation Test

Sample Description	pH	1-hr Settled Volume (ml)
Mixing Tank	7.10	NM
Diluted	7.40	5.8

*NM = Not measured

7.6   EFFECT OF CONCENTRATION OF GENERATED PRECIPITATES ON SETTLING CHARACTERISTICS

Initial particulate generation runs showed that, after dilution, highly concentrated precipitates settled at atypically high rates. Therefore, bench scale testing was performed to determine the settling characteristic of generated precipitates as a function of mix tank concentration. For aluminum oxyhydroxide, solutions of 11, 16.5 and 22 grams per liter were prepared. The concentrated solutions were diluted to 2.2 grams per liter. For calcium phosphate, solutions of 5, 10, 15 and 20 grams per liter were prepared, and then diluted to 1 gram per liter. The settling rates of the resultant particulate mixtures were measured in 10-ml settling tubes. The results of these tests are shown in Figures 7.6-1 and 7.6-2. These results show that to achieve reasonably prototypical setting behavior, the mix tank concentration of aluminum oxyhydroxide should not exceed 11 grams per liter, and the mix tank concentration of calcium phosphate should not exceed 5 grams per liter.

Figure 7.6-1: Settling Rate of 2.2 g/L AlOOH as a Function of Mix Tank Concentration
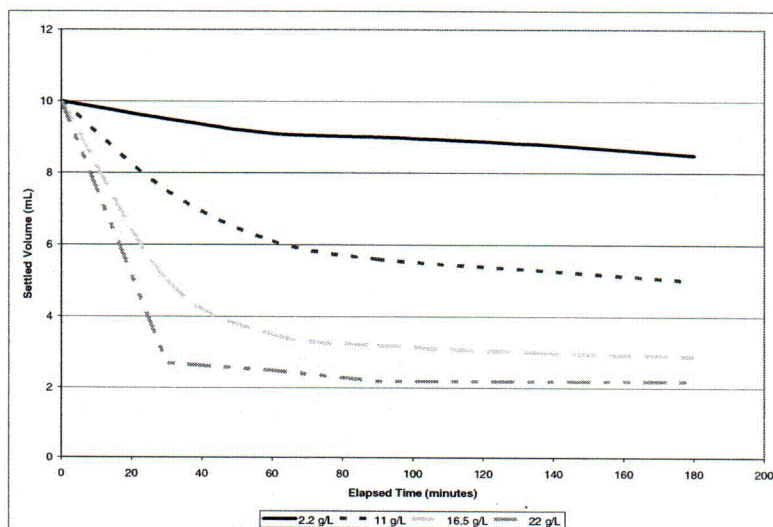
Figure 7.6-2: Settling Rate of 1.0 g/L Calcium Phosphate as a Function of Mix Tank Concentration
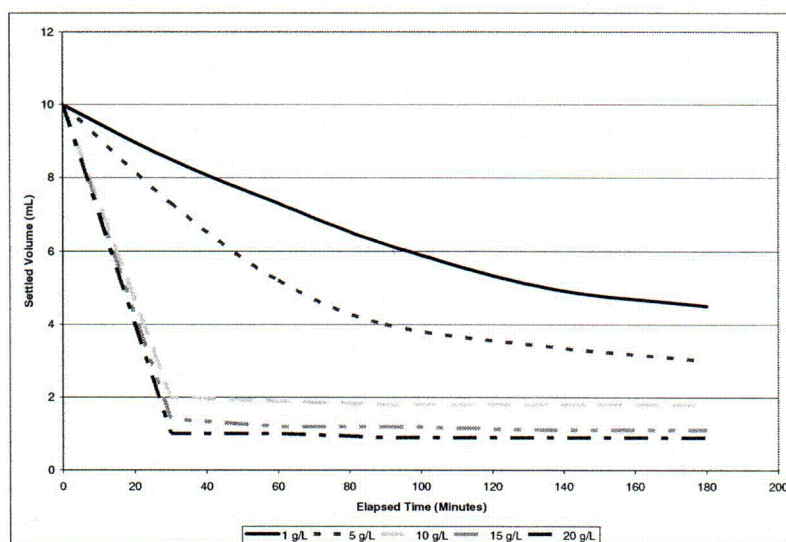
7.7 CONCLUSIONS FROM PARTICULATE GENERATOR TESTS

Testing of the particulate generator demonstrated that simulated particulates can be successfully generated for use in sump screen testing. Generation of the particulates is generally straightforward, and can be performed using readily available equipment and materials. The testing confirmed that the quality and temperature of the water used to prepare the particulates, and that used in the screen test loop, is not critical. No special water chemistry control is required to use the generated particulates in screen testing. The most critical parameter determined during the testing was the limitation on the degree of concentration of the particulates in the mixing tank. In the event that large quantities of particulates are required, the particulates may be prepared in batches or in multiple mixing tanks.

7.8 CRITERIA FOR ALTERNATIVE PRECIPITATES TO BE USED IN SCREEN TESTING

In the event a vendor desires to use alternative materials, the 1-hour settling rate and filtration characteristics of the proposed alternatives must be determined and be verified to meet the minimum acceptance criteria provided in Table 7.8-1. In such cases, it may be necessary to pre-soak the material in water for several hours/days to ensure the proper degree of hydration is obtained.

Table 7.8-1: Minimum Physical Characteristics of Surrogate Precipitates

Precipitate	1-hour Settled Volume (ml)	Metal Concentration (ppm)	Filterability K_f
Sodium Aluminum Silicate	>4.0	1000 ppm Al Equivalent	0.19
Calcium Phosphate	>4.0	400 ppm Ca Equivalent	0.03
Aluminum Oxyhydoxide	>4.0	1000 ppm Al Equivalent	0.20

8.0   PLANT-SPECIFIC APPLICATION

8.1   TRANSITION TO SCREEN VENDOR TESTING

Each plant, given their plant-specific containment material concentrations, pH, and temperatures post-accident, can use the enclosed information to determine the types and amounts of chemical precipitates which may form and be exposed to the sump screen.

In order for plants to utilize the bench testing results, a spreadsheet containing the chemical model developed to allow for a plant-specific prediction of precipitate formation is provided. Guidance is given in Section 8.2 for utility engineers to input their plant-specific containment material amounts, recirculation water volume, post-accident sump and spray pH transients, post-accident sump and spray temperature transients, and to indicate if trisodium phosphate (TSP) is used as a buffering agent. A key issue in a plant's use of the chemical model is the accuracy of the input, especially the temperature and pH transients post-accident.

Once this input has been supplied, the chemical model predicts the types and amounts of precipitates formed given a plant's post-accident conditions. The main chemical precipitates of concern per the WOG chemical effects testing are aluminum oxyhydroxide, sodium aluminum silicate, and calcium phosphate. Aluminum oxyhydroxide is a concern for all plants which contain aluminum either impacted by the spray or submerged in the containment sump pool; however, for plants with high silicon releases, i.e., large amounts of fiberglass, sodium aluminum silicate may be formed instead of aluminum oxyhydroxide and thus is present in larger quantities. Note that calcium phosphate is only a concern for plants which use TSP as a buffering agent.

The chemical model output yields the types and amounts of chemical precipitates which should be included in plant-specific testing of replacement sump screens. Screen vendors may either obtain surrogates for the precipitates for screen testing or generate the precipitates per the guidance provided in Section 7.0. Section 7.0 contains both a description of the equipment setup and the chemical recipes necessary to generate the precipitates formed during the chemical effects bench testing. If screen vendors choose to use surrogate materials for screen testing, additional testing such as settling and pressure drop tests must be performed to confirm that the behavior of the surrogates meets the criteria provided in Section 7.8.

The chemical model predicts the total amount and types of precipitates which may form post-accident under plant-specific conditions. Once representative precipitates have been obtained, the amount of precipitates for use in screen testing should be scaled to the size of the test screen, similar to the method used for any other debris source. Then the impact of the precipitates on screen head loss may be evaluated.

8.2   DIRECTIONS FOR USE OF CHEMICAL MODEL

This section provides directions for plant-specific use of the chemical model to predict the quantity and types of precipitates which may form post-accident. See Appendix D for the detailed equations used in the chemical model spreadsheet.

The first several worksheets of the supplied Excel file are the only ones for which plant-specific data needs to be input. The later worksheets are used to calculate the mass release of the aluminum, calcium, and silicon from the containment materials. From these mass releases, the quantity of each precipitate formed is determined in the "Results Table" spreadsheet from the most chemically stable compounds. The material sources of the elemental mass releases are shown in the "Releases by Material" spreadsheet, and the material sources for the total mass of precipitates which may form are shown in the "Precipitate by Material" spreadsheet.

Worksheet = Instructions

The first worksheet in the spreadsheet provides instructions for filling out the three subsequent spreadsheets with the plant-specific time-temperature and time-pH profiles, the containment material volumes exposed post-accident, and any required plant-specific material density values.

Worksheet = Time Temp pH Input

This worksheet is used to enter the time-temperature profiles, including sump and steam temperature, and time-pH profile in containment post-accident. The values in red on the worksheet should be replaced with plant-specific values. The level of detail is dependent upon that of the plant-specific information. A sensitivity discussion is included in Section 6.5 to evaluate the effect of input variable error on the results.

Column A contains the time in seconds which corresponds to the changing pH and sump and steam temperatures. The time from the beginning of the accident should be entered within the 35 rows. Column B converts this time to minutes by dividing each row entry by 60 sec/min, while Column C then converts to hours by dividing by 60 min/hr. Finally, Column D converts the time to days by dividing by 24 hr/day. In this example calculation, the chemical effects are considered for 30 days following the accident.

Columns E and F contain the sump pH and sump temperature values, respectively, at the corresponding times in Columns A-D. Similarly, Columns H and I contain the data for the spray pH and containment temperature. The entered sump and spray pH values in Columns E and H should be corrected to 25 °C. Most pH calculations have already corrected the pH values to 25 °C. The model assumes that all surfaces which are in contact with the spray are at the containment temperature entered in Column I.

The chemical effects model was developed using data that covered the temperature range of 185°F to 270°F. The model will extrapolate the data to higher or lower temperatures, but correct operation outside of the range has not been verified. Likewise, the pH range of 4.1 to 12 was used in model development, and any use of the model outside this range is not recommended without additional verification.

Column G presents the option to allow the elemental mass already released into the sump solution to impact the dissolution rate from each material containing that element. In order to take credit for this effect on the dissolution rate, the sump solution must be mixed, which is assumed in this example to occur approximately 1 hour after the start of recirculation.

The notes provide guidance on the post-accident transient. For this example, reactor coolant system (RCS) blowdown is assumed to occur at 6 seconds or 0.1 minutes. After RCS blowdown, the temperature of the RCS water dominates the steam temperature and thus influences the pH. Blowdown is assumed to be complete at 180 seconds or 3 minutes. The injection phase starts shortly after at 200 seconds. At this point, the moisture outside of the sump is mostly made up of the containment spray, so the containment temperature is assumed to be that of the spray solution.

The injection phase continues until 1800 seconds or 30 minutes when the recirculation phase begins. Correspondingly, the sump temperature and steam temperature begin to drop significantly. The spray is terminated 4 hours into the transient, while recirculation continues until the end of the calculation. For plants with a different spray duration, the data in Columns H and I may be extended or shortened depending on the length of the spray phase.

Note that if data is entered over a different range of cells than is shown in the example, the worksheets referencing this data must all be changed by adding or subtracting rows accordingly. The easiest approach at this time is to adjust the data to fit into example cell range.

Worksheet = Materials Input

This worksheet is used to input the containment material data, such as that requested on the plant survey, and the recirculation water volume. The materials are divided into the material classes determined for testing. Also, there is a flag to indicate whether or not trisodium phosphate (TSP) is used as a buffering agent.

Column A lists the material classes developed to sort the containment materials by chemical composition. Column B lists the materials within each class. Finally, the amount of each material should be input in Column C using the units listed in Column B. For the insulation material volumes and the exposed concrete surface area, the amount input should be the total amount of material which is either transported to the sump pool or submerged in the sump pool.

Note that if there is a significant amount of concrete debris/dust assumed to be formed, the mass of this concrete debris may be converted to a corresponding surface area using the specific surface area given in Section 5.1.2.1 to be 9.24 m^2/g. The surface area of this concrete debris can then be added to the exposed surface area of the undamaged concrete.

The model assumes that the amount of precipitate generated from the insulation materials and concrete exposed to the spray will not contribute significantly to the total amount of precipitate formed from the submerged materials. The limited amount of precipitate which does form due to exposure to the spray is expected to become captured within the material and hence will not be transported to the sump pool and subsequently to the sump screen. Alternatively, the model may be rerun with the amount of materials exposed to the spray to determine the additional amount of precipitate formed. If this method is used, the spray ph and temperature profiles must be entered in the columns for the sump pH and temperature.

The aluminum surface area input is separated into two categories: the surface area exposed to the spray (aluminum not-submerged) and the surface area submerged in the sump pool. There is no difference in the corrosion rates for these two categories of aluminum; however, the two categories are exposed to

different pH and temperature profiles affecting the rate of dissolution. For each category of aluminum the mass corresponding to the surface area input should be entered if available. Inputting the aluminum mass limits the total aluminum release to that available. If the mass is not known, a large number may be entered for conservatism.

The sump pool volume should also be entered in Column C. Alternatively, if the total mass of the coolant in the Emergency Core Cooling System (ECCS) is known, this value should be entered in the "Materials Conversions" spreadsheet. Note, for the sump pool volume, sensitivities should be run with both the minimum and maximum recirculation volume in order to determine the more limiting case for each precipitate generated. Sensitivities show that using the minimum recirculation water volume may result in a larger aluminum oxyhydroxide mass, while the maximum recirculation volume provides for greater masses of calcium phosphate and sodium aluminum silicate.

Worksheet = Materials Conversions

This worksheet converts the material amounts input in the previous worksheet to mass for all materials but the aluminum for which the mass was entered on the previous worksheet. The mass (lb) is converted to kg by dividing by the conversion factor of 2.2046 lb/kg. The material densities are obtained from NEI 04-07 (Reference 8.2-1). If these density values are not consistent with plant-specific requirements, the density values may be changed to those required. Once each insulation material volume is converted into mass, the masses in each material class are summed to provide a total plant-specific mass for each tested material.

The recirculation sump pool volume is also converted to mass in this worksheet using the density of boric acid at 185°F. If plants do not know the mass of the recirculation water and hence cannot enter it in Column E, then the density of water at the temperature at which the sump pool volume was determined should be used.

Worksheet = Results Table

This worksheet presents the elemental releases as a function of time. The releases are calculated in the subsequent worksheets. See Appendix D for a description of the detailed calculations. The major elements modeled are calcium, silicon and aluminum. The worksheet also determines as a function of time the precipitates which may form from the elemental mass releases. For all buffering agents, sodium aluminum silicate and aluminum oxyhydroxide precipitates may form; however, the quantity of each precipitate as a function of time is impacted by the different pH profiles. Note that if silicon is present in much larger quantities than aluminum, i.e., silicon mass > 2.9 * aluminum mass, sodium aluminum silicate is more likely to form than aluminum oxyhydroxide. Also, calcium phosphate precipitate only forms if the flag which indicates that TSP is used as a buffering agent is selected in the "Materials Input" worksheet.

Worksheet = Releases by Material

This worksheet illustrates which material classes contribute to the total elemental releases tabulated in the "Results Table" worksheet. The elemental releases in kilograms from each containment material are

tabulated. A column chart showing the contributions from each material to the total elemental mass release is also presented.

<u>Worksheet = Precipitate by Material</u>

Similarly to the previous worksheet, this worksheet illustrates which material classes contribute to the precipitate mass determined in the "Results Table" worksheet. The mass of the precipitates in kilograms which form from each material source is tabulated. A column chart showing the contributions from each material to the total precipitate mass release is also presented.

This worksheet, in combination with the "Releases by Material" worksheet, has been provided to assist plants in better determining which containment materials contribute to the types and quantities of precipitate formed in order to explore potential mitigation strategies.

8.2.1 Reference

8.2-1   NEI 04-07, Revision 0, "Pressurized Water Reactor Sump Performance Evaluation Methodology," December 2004.

APPENDIX A: BENCH TEST DISSOLUTION RESULTS

This appendix contains two tables. Table A-1 contains sample measured pH values as well as concentration of dissolved species determined by ICP. Table A-2 contains sample areas and masses, mass losses, and calculated dissolution rates. Runs corresponding to the design test matrix are listed with no shading, while replicate runs are shaded. The key to the column contents follows. Release rates were based on solution concentrations rather than material mass loss since the recovery of some materials from the reactor was difficult.

Variable	Units	Description
Material	none	The containment material that was tested
pHa	none	Initial pH of the simulated coolant introduced into the reactor
pHb	none ·	pH of the simulated coolant measured after a given reaction time
T	F	Target temperature of the reactor
Time	sec	Elapsed time between start of reaction and sampling
Al	ppm	Aluminum concentration in simulated coolant sample
Ca	ppm	Calcium concentration in simulated coolant sample
Mg	ppm	Magnesium concentration in simulated coolant sample
P	ppm	Phosphorus concentration in simulated coolant sample
S	ppm	Sulfur concentration in simulated coolant sample
Si	ppm	Silicon concentration in simulated coolant sample
Zn	ppm	Zinc concentration in simulated coolant sample
Fe	ppm	Iron concentration in simulated coolant sample
Surf. Area	cm^2	Surface area of test coupon or in the case of concrete, the particle surface area
Mat. Start Mass	g	Starting mass of material placed in the reactor
Mass Loss	g	Mass of material lost from dissolution in the reactor and handling loss
Al Rel Rate/Mass	mg/kg-min	Aluminum release rate from solution concentration change normalized to material mass (used for insulation materials)
Ca Rel Rate/Mass	mg/kg-min	Calcium release rate from solution concentration change normalized to material mass
Si Rel Rate/Mass	mg/kg-min	Silicon release rate from solution concentration change normalized to material mass
S Rel Rate/Mass	mg/kg-min	Sulfur release rate from solution concentration change normalized to material mass
Al Rel Rate/Area	mg/m^2-min	Aluminum release rate from solution concentration change normalized to material area
Fe Rel Rate/Area	mg/m^2-min	Iron release rate from solution concentration change normalized to material area
Zn Rel Rate/Area	mg/m^2-min	Zinc release rate from solution concentration change normalized to material area

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
E5-1	Al Sheet	4.1	6.7	190	30	15.2	1.6	0.0	0.0	0.0	0.8	NT	NT
E5-2	Al Sheet	4.1	5.7	190	60	0.5	1.7	0.0	0.0	0.0	1.2	NT	NT
E5-3	Al Sheet	4.1	5.2	190	90	0.5	1.8	0.0	0.0	0.0	0.7	NT	NT
C5-1	Al Sheet	8	8.1	190	30	17.8	0.0	0.0	0.0	0.2	2.4	NT	NT
C5-2	Al Sheet	8	8.3	190	60	51.4	0.0	0.0	0.0	0.0	1.1	NT	NT
C5-3	Al Sheet	8	8.3	190	90	99.9	0.0	0.0	0.0	0.0	1.1	NT	NT
Q7-1	Al Sheet	8	8.1	190	30	42.0	3.2	0.1	0.0	0.8	4.6	NT	NT
Q7-2	Al Sheet	8	8.1	190	60	68.6	2.4	0.1	0.0	0.6	5.6	NT	NT
Q7-3	Al Sheet	8	8.1	190	90	116.0	2.1	0.1	0.0	0.5	3.3	NT	NT
D5-1	Al Sheet	12	10.9	190	30	607.3	0.0	0.0	0.0	0.3	1.1	NT	NT
D5-2	Al Sheet	12	11.6	190	60	914.2	0.0	0.0	0.0	0.4	6.3	NT	NT
D5-3	Al Sheet	12	11.5	190	90	1152.4	0.0	0.0	0.0	0.2	0.6	NT	NT
K7-1	Al Sheet	4.1	6.3	265	30	2.1	NT	NT	NT	NT	NT	NT	NT
K7-2	Al Sheet	4.1	6.0	265	60	3.8	NT	NT	NT	NT	NT	NT	NT
K7-3	Al Sheet	4.1	5.3	265	90	6.4	NT	NT	NT	NT	NT	NT	NT
N7-1	Al Sheet	8	8.1	265	30	211.7	2.1	0.1	0.0	1.3	12.2	NT	NT
N7-2	Al Sheet	8	8.1	265	60	413.4	1.8	0.1	0.0	0.0	9.8	NT	NT
N7-3	Al Sheet	8	8.1	265	90	569.2	1.2	0.0	0.0	0.0	8.7	NT	NT
S7-1	Al Sheet	12	11.4	265	30	16275.0	NT	NT	NT	NT	NT	NT	NT
S7-2	Al Sheet	12	11.5	265	60	29680.0	NT	NT	NT	NT	NT	NT	NT
S7-3	Al Sheet	12	11.6	265	90	13155.0	NT	NT	NT	NT	NT	NT	NT
P4-1	Blank	4.1	5.7	190	30	0.8	1.9	0.1	0.0	0.0	0.1	0.4	0.2
P4-2	Blank	4.1	5.8	190	60	0.8	0.9	0.0	0.0	0.0	0.0	0.2	0.1
P4-3	Blank	4.1	5.8	190	90	0.9	1.0	0.0	0.0	0.0	0.0	0.6	0.2
N4-1	Blank	12	12.1	265	30	13.0	1.6	0.0	0.0	0.8	28.2	NT	NT
N4-2	Blank	12	12.1	265	60	8.6	1.1	0.0	0.0	0.7	23.7	NT	NT
N4-3	Blank	12	12.1	265	90	9.0	1.2	0.0	0.0	0.6	21.2	0.0	0.7
B5-1	Calsil	4.1	6.9	190	30	1.3	194.5	0.2	0.0	42.5	186.3	NT	NT
B5-2	Calsil	4.1	6.9	190	60	1.6	214.7	0.2	0.0	31.0	190.1	NT	NT
B5-3	Calsil	4.1	6.9	190	90	1.5	212.9	0.2	0.0	26.5	188.1	NT	NT
B6-1	Calsil	4.1	6.6	190	30	2.0	160.7	0.1	0.0	23.2	163.1	NT	NT
B6-2	Calsil	4.1	6.7	190	60	2.2	203.4	0.1	0.0	14.6	187.8	NT	NT
B6-3	Calsil	4.1	6.8	190	90	2.3	236.4	0.2	0.0	13.8	215.7	NT	NT
B7-1	Calsil	4.1	6.8	190	30	1.3	132.2	0.1	0.0	33.3	125.6	NT	NT
B7-2	Calsil	4.1	6.9	190	60	1.9	229.3	0.2	0.0	51.2	239.4	NT	NT
B7-3	Calsil	4.1	6.9	190	90	1.8	227.0	0.2	0.0	38.2	231.5	NT	NT
B8-1	Calsil	4.1	6.46	190	30	1.2	108.2	0.1	0.0	12.8	100.0	NT	NT
B8-2	Calsil	4.1	6.54	190	60	2.4	138.0	0.1	0.0	16.1	132.5	NT	NT
B8-3	Calsil	4.1	6.6	190	90	2.5	162.7	0.1	0.0	16.1	150.4	NT	NT
E3-1	Calsil	4.1	6.6	190	30	2.3	138.7	0.1	0.0	11.5	120.4	NT	NT

							Table A-1: Test Matrix and Measured Concentrations by ICP						
Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
E3-2	Calsil	4.1	6.6	190	60	2.9	136.3	0.1	0.0	9.1	113.3	NT	NT
E3-3	Calsil	4.1	6.6	190	90	2.7	137.2	0.1	0.0	7.9	108.7	NT	NT
C2-1	Calsil	8	8.1	190	30	1.4	0.0	0.0	0.0	0.0	5.7	NT	NT
C2-2	Calsil	8	8.4	190	60	1.1	74.7	0.1	0.0	27.2	158.1	NT	NT
C2-3	Calsil	8	8.5	190	90	0.9	58.5	0.1	0.0	15.7	133.7	NT	NT
R7-1	Calsil	8	8.2	190	30	2.5	33.8	0.1	0.0	43.9	280.5	NT	NT
R7-2	Calsil	8	8.2	190	60	1.5	36.9	0.1	0.0	42.2	330.8	NT	NT
R7-3	Calsil	8	8.2	190	90	1.5	38.6	0.1	0.0	42.1	377.9	NT	NT
P8-1	Calsil	12	11.6	190	30	5.9	9.6	0.0	0.1	18.8	340.2	NT	NT
P8-2	Calsil	12	11.6	190	60	6.3	7.4	0.0	0.1	12.0	305.9	NT	NT
P8-3	Calsil	12	11.5	190	90	0.7	9.5	0.0	0.1	24.9	242.4	NT	NT
K2-1	Calsil	4.1	7.0	265	30	0.8	36.6	0.1	0.0	14.4	104.9	NT	NT
K2-2	Calsil	4.1	7.9	265	60	0.7	48.4	0.0	0.0	12.1	119.5	NT	NT
K2-3	Calsil	4.1	6.8	265	90	0.8	49.3	0.1	0.0	7.3	94.4	NT	NT
H2-1	Calsil	8		265	30	1.2	10.0	0.0	0.0	7.5	106.5	NT	NT
H2-2	Calsil	8		265	60	1.1	10.5	0.0	0.0	7.8	124.1	NT	NT
H2-3	Calsil	8		265	90	1.2	11.4	0.0	0.0	7.2	129.6	NT	NT
L2-1	Calsil	8	8.1	265	30	0.6	13.6	0.0	0.0	8.6	82.1	NT	NT
L2-2	Calsil	8	8.1	265	60	1.3	19.6	0.0	0.0	14.9	130.8	NT	NT
L2-3	Calsil	8	8.1	265	90	0.9	12.5	0.0	0.0	6.8	80.4	NT	NT
M2-1	Calsil	12	10.9	265	30	1.7	1.8	0.0	0.1	31.1	243.8	NT	NT
M2-2	Calsil	12	11.0	265	60	2.6	2.0	0.0	0.1	19.3	239.3	NT	NT
M2-3	Calsil	12	11.3	265	90	5.1	2.2	0.0	0.1	10.7	231.5	NT	NT
E8-1	Concrete	4.1	6.5	190	30	7.1	439.3	0.2	0.0	7.8	33.0	NT	NT
E8-2	Concrete	4.1	6.5	190	60	1.4	484.3	0.2	0.0	7.4	36.2	NT	NT
E8-3	Concrete	4.1	6.5	190	90	1.1	424.4	0.2	0.0	6.7	29.7	NT	NT
Q1-1	Concrete	4.1	6.5	190	30	10.5	165.4	0.1	0.0	25.4	38.2	NT	NT
Q1-2	Concrete	4.1	6.5	190	60	8.7	155.8	0.1	0.0	16.5	30.2	NT	NT
Q1-3	Concrete	4.1	6.4	190	90	7.0	143.6	0.1	0.0	12.4	30.9	NT	NT
C8-1	Concrete	8	8.1	190	30	2.6	93.8	0.1	0.0	9.7	15.1	NT	NT
C8-2	Concrete	8	8.2	190	60	2.4	118.6	0.1	0.0	16.6	19.3	NT	NT
C8-3	Concrete	8	8.4	190	90	2.1	117.9	0.1	0.0	16.5	18.7	NT	NT
R1-1	Concrete	8	8.1	190	30	6.6	36.2	0.1	0.1	4.6	34.8	NT	NT
R1-2	Concrete	8	8.1	190	60	6.2	35.1	0.1	0.1	4.2	33.2	NT	NT
R1-3	Concrete	8	8.1	190	90	7.6	43.4	0.1	0.1	5.4	40.6	NT	NT
D8-1	Concrete	12	12.0	190	30	8.1	64.0	0.0	0.0	11.4	16.8	NT	NT
D8-2	Concrete	12	12.0	190	60	12.8	95.8	0.0	0.0	19.5	24.0	NT	NT
D8-3	Concrete	12	12.1	190	90	15.1	102.6	0.0	0.0	20.3	26.4	NT	NT
K5-1	Concrete	4.1	6.7	265	30	7.6	120.0	0.1	0.0	2.5	17.7	NT	NT
K5-2	Concrete	4.1	6.4	265	60	4.4	97.3	0.1	0.0	1.5	18.0	NT	NT

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
K5-3	Concrete	4.1	6.3	265	90	4.1	97.7	0.1	0.0	1.4	24.4	NT	NT
L5-1	Concrete	8	8.0	265	30	11.4	57.7	0.1	0.0	5.0	20.5	NT	NT
L5-2	Concrete	8	8.1	265	60	13.9	67.3	0.1	0.0	5.5	24.7	NT	NT
L5-3	Concrete	8	8.1	265	90	13.0	64.5	0.1	0.0	5.3	24.3	NT	NT
M5-1	Concrete	12	12.2	265	30	45.4	43.9	0.0	0.0	31.5	48.8	NT	NT
M5-2	Concrete	12	12.2	265	60	43.0	45.6	0.0	0.0	30.8	44.2	NT	NT
M5-3	Concrete	12	12.2	265	90	25.5	59.4	0.0	0.0	31.6	50.7	NT	NT
B3-1	Durablanket	4.1	4.46	190	30	0.7	0.0	0.0	0.0	0.0	0.3	NT	NT
B3-2	Durablanket	4.1	4.42	190	60	0.7	0.0	0.0	0.0	0.0	0.7	NT	NT
B3-3	Durablanket	4.1	4.5	190	90	0.7	0.0	0.0	0.0	0.0	0.6	NT	NT
E2-1	Durablanket	4.1	4.5	190	30	0.1	1.7	0.0	0.0	0.0	1.0	NT	NT
E2-2	Durablanket	4.1	4.5	190	60	0.0	1.7	0.0	0.0	0.0	0.9	NT	NT
E2-3	Durablanket	4.1	4.5	190	90	0.0	1.5	0.0	0.0	0.0	0.9	NT	NT
C3-1	Durablanket	8	8.1	190	30	5.2	0.0	0.0	0.0	0.0	8.0	NT	NT
C3-2	Durablanket	8	8.2	190	60	13.3	0.0	0.0	0.0	0.0	20.8	NT	NT
C3-3	Durablanket	8	8.3	190	90	17.0	0.0	0.0	0.0	0.0	28.8	NT	NT
Q4-1	Durablanket	8	5.1	190	30	1.1	1.5	0.1	0.0	0.3	2.8	NT	NT
Q4-2	Durablanket	8	4.7	190	60	1.2	1.3	0.1	0.0	0.4	1.7	NT	NT
Q4-3	Durablanket	8	4.7	190	90	1.5	1.4	0.1	0.0	0.3	2.4	NT	NT
R4-1	Durablanket	8	8.1	190	30	3.4	6.5	0.0	0.0	1.1	12.1	NT	NT
R4-2	Durablanket	8	8.0	190	60	5.8	7.6	0.0	0.0	1.1	8.0	NT	NT
R4-3	Durablanket	8	8.1	190	90	4.8	6.1	0.0	0.0	0.8	6.3	0.0	0.0
D3-1	Durablanket	12	12.0	190	30	4.3	0.0	0.0	0.0	0.1	9.6	NT	NT
D3-2	Durablanket	12	12.0	190	60	17.8	0.0	0.0	0.0	0.3	43.6	NT	NT
D3-3	Durablanket	12	12.0	190	90	24.1	0.0	0.0	0.0	0.3	59.7	NT	NT
K1-1	Durablanket	4.1	6.3	265	30	2.0	5.2	0.0	0.0	0.0	6.6	NT	NT
K1-2	Durablanket	4.1	5.4	265	60	1.7	6.2	0.0	0.0	0.0	8.1	NT	NT
K1-3	Durablanket	4.1	5.9	265	90	1.4	4.2	0.0	0.0	0.0	5.9	NT	NT
O4-1	Durablanket	4.1	5.4	265	30	2.6	2.4	0.1	0.0	0.0	9.0	NT	NT
O4-2	Durablanket	4.1	5.9	265	60	3.1	1.5	0.1	0.0	0.0	8.7	NT	NT
O4-3	Durablanket	4.1	5.4	265	90	4.0	1.1	0.1	0.0	0.0	10.7	NT	NT
L1-1	Durablanket	8	8.0	265	30	6.8	1.1	0.0	0.0	0.0	8.2	NT	NT
L1-2	Durablanket	8	8.1	265	60	14.6	1.2	0.0	0.0	0.0	19.1	NT	NT
L1-3	Durablanket	8	8.0	265	90	25.2	1.6	0.0	0.0	0.0	32.8	NT	NT
M1-1	Durablanket	12	12.0	265	30	29.1	0.5	0.0	0.0	0.2	38.5	NT	NT
M1-2	Durablanket	12	12.0	265	60	21.4	0.4	0.0	0.0	0.3	27.0	NT	NT
M1-3	Durablanket	12	12.0	265	90	38.2	0.4	0.0	0.0	0.3	71.3	NT	NT
E6-1	Fiberglass	4.1	5.8	190	30	0.3	4.0	0.1	0.0	2.2	5.4	NT	NT
E6-2	Fiberglass	4.1	5.2	190	60	0.0	2.2	0.0	0.0	1.1	0.9	NT	NT
E6-3	Fiberglass	4.1	5.3	190	90	0.0	3.1	0.1	0.0	1.1	1.2	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
Q3-1	Fiberglass	4.1	5.4	190	30	1.0	2.4	0.1	0.0	6.1	4.8	NT	NT
Q3-2	Fiberglass	4.1	5.4	190	60	0.9	2.3	0.1	0.0	4.9	5.2	NT	NT
Q3-3	Fiberglass	4.1	5.4	190	90	1.1	2.6	0.2	0.0	4.2	6.4	NT	NT
C6-1	Fiberglass	8	8.1	190	30	1.0	0.5	0.1	0.0	5.0	9.1	NT	NT
C6-2	Fiberglass	8	8.2	190	60	1.2	1.0	0.1	0.0	5.2	20.4	NT	NT
C6-3	Fiberglass	8	8.3	190	90	1.5	2.7	0.2	0.0	5.5	36.0	NT	NT
R3-1	Fiberglass	8	8.1	190	30	4.2	6.0	0.1	0.0	8.8	14.1	NT	NT
R3-2	Fiberglass	8	8.1	190	60	4.0	7.4	0.1	0.0	8.9	27.1	NT	NT
R3-3	Fiberglass	8	8.1	190	90	3.9	7.6	0.1	0.0	7.1	39.3	NT	NT
D6-1	Fiberglass	12	11.9	190	30	2.5	6.8	0.0	0.0	2.6	74.3	NT	NT
D6-2	Fiberglass	12	12.0	190	60	4.0	17.6	0.0	0.0	2.9	171.2	NT	NT
D6-3	Fiberglass	12	12.0	190	90	4.9	24.8	0.0	0.0	3.4	233.3	NT	NT
K4-1	Fiberglass	4.1	6.4	265	30	4.2	9.1	0.1	0.0	1.2	33.7	NT	NT
K4-2	Fiberglass	4.1	6.1	265	60	2.4	14.3	0.3	0.0	0.6	75.0	NT	NT
K4-3	Fiberglass	4.1	6.2	265	90	1.7	19.8	0.4	0.0	0.4	110.0	NT	NT
L4-1	Fiberglass	8	8.0	265	30	2.7	4.8	0.2	0.0	2.7	42.2	NT	NT
L4-2	Fiberglass	8	8.1	265	60	3.2	8.2	0.2	0.0	2.5	61.2	NT	NT
L4-3	Fiberglass	8	8.1	265	90	3.8	11.2	0.2	0.0	2.4	85.5	NT	NT
M4-1	Fiberglass	12	12.0	265	30	6.7	9.7	0.0	0.0	5.9	171.0	NT	NT
M4-2	Fiberglass	12	12.0	265	60	8.3	13.6	0.0	0.0	4.5	214.9	NT	NT
M4-3	Fiberglass	12	12.0	265	90	8.6	7.1	0.0	0.0	3.7	222.7	NT	NT
P2-1	Galvanized	4.1	5.9	190	30	NT	NT	NT	NT	NT	NT	2.9	0.8
P2-2	Galvanized	4.1	5.8	190	60	NT	NT	NT	NT	NT	NT	4.9	1.0
P2-3	Galvanized	4.1	5.8	190	90	NT	NT	NT	NT	NT	NT	6.9	1.1
Q6-1	Galvanized	8	8.1	190	30	NT	NT	NT	NT	NT	NT	0.0	0.0
Q6-2	Galvanized	8	8.1	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
Q6-3	Galvanized	8	8.1	190	90	NT	NT	NT	NT	NT	NT	0.1	0.0
P6-1	Galvanized	12	12.0	190	30	NT	NT	NT	NT	NT	NT	2.3	0.0
P6-2	Galvanized	12	12.0	190	60	NT	NT	NT	NT	NT	NT	3.2	0.0
P6-3	Galvanized	12	12.1	190	90	NT	NT	NT	NT	NT	NT	4.5	0.2
O2-1	Galvanized	4.1	5.4	265	30	NT	NT	NT	NT	NT	NT	1.0	0.8
O2-2	Galvanized	4.1	5.4	265	60	NT	NT	NT	NT	NT	NT	1.9	0.1
O2-3	Galvanized	4.1	5.5	265	90	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-1	Galvanized	8	8.1	265	30	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-2	Galvanized	8	8.2	265	60	NT	NT	NT	NT	NT	NT	0.0	0.0
N6-3	Galvanized	8	8.1	265	90	NT	NT	NT	NT	NT	NT	0.1	0.0
N2-1	Galvanized	12	12.1	265	30	NT	NT	NT	NT	NT	NT	7.1	0.7
N2-2	Galvanized	12	12.1	265	60	NT	NT	NT	NT	NT	NT	12.4	0.7
N2-3	Galvanized	12	12.1	265	90	NT	NT	NT	NT	NT	NT	15.2	0.4
P3-1	Interam	4.1	4.8	190	30	0.7	1.1	0.0	0.0	0.0	0.0	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
P3-2	Interam	4.1	4.7	190	60	0.7	0.6	0.0	0.0	0.0	0.0	NT	NT
P3-3	Interam	4.1	4.7	190	90	0.7	0.6	0.0	0.0	0.0	0.0	NT	NT
Q8-1	Interam	8	8.1	190	30	8.1	6.2	0.1	0.0	0.9	8.1	NT	NT
Q8-2	Interam	8	8.1	190	60	10.5	2.9	0.1	0.0	0.7	6.3	NT	NT
Q8-3	Interam	8	8.1	190	90	7.6	3.3	0.0	0.0	0.7	4.8	NT	NT
P7-1	Interam	12	12.0	190	30	161.1	3.1	0.0	0.0	0.6	22.3	NT	NT
P7-2	Interam	12	12.0	190	60	61.4	3.0	0.0	0.0	0.9	17.2	NT	NT
P7-3	Interam	12	12.0	190	90	83.5	2.5	0.0	0.0	0.5	12.2	NT	NT
O3-1	Interam	4.1	5.4	265	30	1.0	1.3	0.1	0.1	0.0	4.0	NT	NT
O3-2	Interam	4.1	5.5	265	60	1.0	0.9	0.1	0.1	0.0	3.1	NT	NT
O3-3	Interam	4.1	5.5	265	90	1.2	0.8	0.1	0.1	0.0	3.3	NT	NT
N8-1	Interam	8	8.1	265	30	5.4	2.9	0.1	0.1	0.5	5.1	NT	NT
N8-2	Interam	8	8.1	265	60	10.1	2.9	0.0	0.1	0.5	5.9	NT	NT
N8-3	Interam	8	8.1	265	90	11.9	2.5	0.0	0.1	0.4	5.0	NT	NT
N3-1	Interam	12	12.1	265	30	35.6	0.4	0.0	0.1	0.3	16.6	NT	NT
N3-2	Interam	12	12.1	265	60	50.6	0.5	0.0	0.1	0.4	23.1	NT	NT
N3-3	Interam	12	12.1	265	90	50.5	0.6	0.0	0.1	0.7	22.7	NT	NT
B4-1	Mineral Wool	4.1	4.6	190	30	0.7	0.0	0.0	0.0	0.0	0.7	NT	NT
B4-2	Mineral Wool	4.1	4.6	190	60	0.7	0.0	0.1	0.0	0.0	1.0	NT	NT
B4-3	Mineral Wool	4.1	4.6	190	90	0.7	0.0	0.1	0.0	0.0	1.0	NT	NT
E4-1	Mineral Wool	4.1	5.7	190	30	0.0	5.5	0.0	0.0	0.0	2.3	NT	NT
E4-2	Mineral Wool	4.1	4.9	190	60	0.0	1.8	0.0	0.0	0.0	1.0	NT	NT
E4-3	Mineral Wool	4.1	4.8	190	90	0.0	1.4	0.0	0.0	0.0	0.8	NT	NT
C4-1	Mineral Wool	8	8.1	190	30	0.9	0.0	0.1	0.0	0.2	2.6	NT	NT
C4-2	Mineral Wool	8	8.3	190	60	1.0	0.0	0.1	0.0	0.1	4.1	NT	NT
C4-3	Mineral Wool	8	8.4	190	90	1.5	0.0	0.2	0.0	0.1	7.4	NT	NT
R6-1	Mineral Wool	8	8.1	190	30	4.3	10.1	0.1	0.0	2.2	8.2	NT	NT
R6-2	Mineral Wool	8	8.1	190	60	5.2	11.3	0.1	0.0	2.3	11.4	NT	NT
R6-3	Mineral	8	8.1	190	90	4.7	10.2	0.1	0.0	1.8	10.5	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP													
Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
	Wool												
D4-1	Mineral Wool	12	12.0	190	30	2.1	2.9	0.0	0.0	0.2	11.4	NT	NT
D4-2	Mineral Wool	12	12.0	190	60	5.1	9.9	0.0	0.0	0.5	32.2	NT	NT
D4-3	Mineral Wool	12	12.0	190	90	7.4	19.3	0.0	0.0	0.6	47.2	NT	NT
K3-1	Mineral Wool	4.1	6.1	265	30	1.3	4.3	0.1	0.0	0.0	4.5	NT	NT
K3-2	Mineral Wool	4.1	5.6	265	60	1.1	6.3	0.1	0.0	0.0	5.3	NT	NT
K3-3	Mineral Wool	4.1	5.7	265	90	2.0	12.0	0.2	0.0	0.0	9.4	NT	NT
H4-1	Mineral Wool	8		265	30	3.1	3.9	0.2	0.0	0.0	10.9	NT	NT
H4-2	Mineral Wool	8		265	60	5.7	7.8	0.3	0.0	0.0	20.1	NT	NT
H4-3	Mineral Wool	8		265	90	5.9	8.7	0.3	0.0	0.0	21.0	NT	NT
L3-1	Mineral Wool	8	8.0	265	30	4.8	13.8	0.2	0.0	0.0	17.3	NT	NT
L3-2	Mineral Wool	8	8.1	265	60	5.4	16.6	0.2	0.0	0.0	19.7	NT	NT
L3-3	Mineral Wool	8	8.0	265	90	4.6	14.6	0.2	0.0	0.0	16.7	NT	NT
M3-1	Mineral Wool	12	12.0	265	30	4.7	1.8	0.0	0.0	0.7	56.8	NT	NT
M3-2	Mineral Wool	12	12.1	265	60	12.0	15.2	0.0	0.0	0.8	67.6	NT	NT
M3-3	Mineral Wool	12	12.1	265	90	10.6	14.5	0.0	0.0	0.5	62.8	NT	NT
E7-1	Min-K	4.1	5.8	190	30	0.0	1.6	0.0	0.0	0.0	2.7	NT	NT
E7-2	Min-K	4.1	4.5	190	60	0.0	1.5	0.0	0.0	0.0	1.0	NT	NT
E7-3	Min-K	4.1	4.5	190	90	0.0	1.3	0.0	0.0	0.0	1.9	NT	NT
Q2-1	MIN-K	4.1	5.0	190	30	1.0	1.9	0.1	0.0	0.3	14.0	NT	NT
Q2-2	MIN-K	4.1	4.9	190	60	0.9	1.2	0.1	0.0	0.4	11.7	NT	NT
Q2-3	MIN-K	4.1	4.9	190	90	1.2	1.7	0.1	0.0	0.4	10.1	NT	NT
C7-1	Min-K	8	8.1	190	30	0.9	0.3	0.0	0.0	0.5	66.4	NT	NT
C7-2	Min-K	8	8.2	190	60	0.9	0.0	0.0	0.0	0.4	125.3	NT	NT
C7-3	Min-K	8	8.1	190	90	0.9	0.0	0.0	0.0	0.3	157.0	NT	NT
R2-1	MIN-K	8	8.0	190	30	1.9	4.5	0.1	0.0	0.6	97.6	NT	NT

Table A-1: Test Matrix and Measured Concentrations by ICP													
Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
R2-2	MIN-K	8	8.0	190	60	1.9	3.6	0.0	0.0	0.5	156.8	NT	NT
R2-3	MIN-K	8	8.0	190	90	2.7	6.2	0.1	0.1	1.0	217.8	NT	NT
D7-1	Min-K	12	12.0	190	30	0.9	0.0	0.0	0.0	0.6	97.9	NT	NT
D7-2	Min-K	12	12.0	190	60	0.9	0.0	0.0	0.0	0.7	120.4	NT	NT
D7-3	Min-K	12	11.9	190	90	1.0	0.0	0.0	0.0	0.9	141.9	NT	NT
K8-1	Min-K	4.1	6.2	265	30	7.4	3.5	0.1	0.0	0.1	33.7	NT	NT
K8-2	Min-K	4.1	5.8	265	60	2.8	1.9	0.1	0.0	0.0	35.5	NT	NT
K8-3	Min-K	4.1	5.3	265	90	0.9	1.7	0.0	0.0	0.0	52.2	NT	NT
L8-1	Min-K	8	8.0	265	30	1.1	2.5	0.0	0.0	0.0	39.7	NT	NT
L8-2	Min-K	8	8.0	265	60	2.9	2.9	0.0	0.0	0.0	66.8	NT	NT
L8-3	Min-K	8	8.1	265	90	1.9	2.4	0.0	0.0	0.0	40.8	NT	NT
M8-1	MIN-K	12	12.1	265	30	1.8	0.8	0.0	0.0	0.5	135.4	NT	NT
M8-2	Min-K	12	12.0	265	60	7.9	1.1	0.0	0.0	0.5	121.0	NT	NT
M8-3	Min-K	12	12.1	265	90	16.6	1.8	0.0	0.0	0.6	99.8	NT	NT
B1-1	Nukon	4.1	5.3	190	30	0.7	0.0	0.7	0.0	2.1	0.9	NT	NT
B1-2	Nukon	4.1	5.4	190	60	0.7	0.0	0.1	0.0	0.9	1.5	NT	NT
B1-3	Nukon	4.1	5.5	190	90	0.7	0.0	0.1	0.0	1.8	2.8	NT	NT
E1-1	Nukon	4.1	5.3	190	30	0.2	3.0	0.1	0.0	1.4	2.7	NT	NT
E1-2	Nukon	4.1	5.4	190	60	0.1	2.5	0.1	0.0	1.5	2.5	NT	NT
E1-3	Nukon	4.1	5.4	190	90	0.0	2.4	0.1	0.0	1.2	2.4	NT	NT
C1-1	Nukon	8	8.1	190	30	0.7	0.0	0.1	0.0	2.0	6.4	NT	NT
C1-2	Nukon	8	8.4	190	60	0.6	0.0	0.0	0.0	0.0	1.5	NT	NT
C1-3	Nukon	8	8.3	190	90	1.0	0.0	0.2	0.0	1.8	19.8	NT	NT
R5-1	Nukon	8	8.1	190	30	4.1	9.7	0.1	0.1	7.0	23.5	NT	NT
R5-2	Nukon	8	8.1	190	60	11.8	10.1	0.1	0.2	6.4	32.4	NT	NT
R5-2	Nukon	8	8.1	190	90	4.9	10.8	0.2	0.0	6.1	46.8	NT	NT
D1-1	Nukon	12	11.91	190	30	0.8	0.0	0.1	0.0	0.4	10.8	NT	NT
D1-2	Nukon	12	11.94	190	60	0.8	0.0	0.0	0.0	0.0	8.3	NT	NT
D1-3	Nukon	12	11.91	190	90	0.7	0.0	0.0	0.0	0.0	4.1	NT	NT
K6-1	Nukon	4.1	6.5	265	30	2.2	5.7	0.1	0.0	0.0	18.0	NT	NT
K6-2	Nukon	4.1	6.0	265	60	0.9	6.7	0.1	0.0	0.0	20.3	NT	NT
K6-3	Nukon	4.1	5.9	265	90	1.0	8.3	0.1	0.0	0.0	30.8	NT	NT
L6-1	Nukon	8	8.0	265	30	2.7	8.3	0.2	0.0	1.2	49.6	NT	NT
L6-2	Nukon	8	8.1	265	60	3.7	17.4	0.2	0.0	1.0	67.0	NT	NT
L6-3	Nukon	8	8.1	265	90	3.8	10.8	0.2	0.0	0.7	68.0	NT	NT
M6-1	Nukon	12	12.0	265	30	10.1	16.0	0.0	0.0	4.4	206.1	NT	NT
M6-2	Nukon	12	12.0	265	60	7.0	10.4	0.0	0.0	2.3	144.0	NT	NT
M6-3	Nukon	12	12.0	265	90	8.1	8.5	0.0	0.0	1.5	191.9	NT	NT
P1-1	Steel	4.1	5.0	190	30	NT	NT	NT	NT	NT	NT	1.8	2.1
P1-2	Steel	4.1	6.2	190	60	NT	NT	NT	NT	NT	NT	1.2	9.3

Run	Material	pHa	pHb	Temp °F	Time min	Al ppm	Ca ppm	Mg ppm	P ppm	S ppm	Si ppm	Zn ppm	Fe ppm
P1-3	Steel	4.1	5.3	190	90	NT	NT	NT	NT	NT	NT	1.1	19.7
Q5-1	Steel	8	8.1	190	30	NT	NT	NT	NT	NT	NT	0.0	0.0
Q5-2	Steel	8	8.0	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
Q5-3	Steel	8	8.0	190	90	NT	NT	NT	NT	NT	NT	0.0	0.0
P5-1	Steel	12	12.0	190	30	NT	NT	NT	NT	NT	NT	0.0	0.1
P5-2	Steel	12	12.0	190	60	NT	NT	NT	NT	NT	NT	0.0	0.0
P5-3	Steel	12	12.1	190	90	NT	NT	NT	NT	NT	NT	0.1	0.1
O1-1	Steel	4.1	5.2	265	30	NT	NT	NT	NT	NT	NT	0.0	0.3
O1-2	Steel	4.1	5.4	265	60	NT	NT	NT	NT	NT	NT	0.0	3.2
O1-3	Steel	4.1	5.7	265	90	NT	NT	NT	NT	NT	NT	0.0	4.5
N5-1	Steel	8	8.0	265	30	NT	NT	NT	NT	NT	NT	NT	0.0
N5-2	Steel	8	8.1	265	60	NT	NT	NT	NT	NT	NT	NT	0.0
N5-3	Steel	8	8.1	265	90	NT	NT	NT	NT	NT	NT	NT	1.1
N1-1	Steel	12	12.1	265	30	NT	NT	NT	NT	NT	NT	NT	0.5
N1-2	Steel	12	12.1	265	60	NT	NT	NT	NT	NT	NT	NT	0.6
N1-3	Steel	12	12.1	265	90	NT	NT	NT	NT	NT	NT	NT	0.6

Table A-1: Test Matrix and Measured Concentrations by ICP

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pHa	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate/Mass mg/kg-min	Al Rel Rate/Area mg/m²-min	Ca Rel Rate/Mass mg/kg-min	Si Rel Rate/Mass mg/kg-min	S Rel Rate/Mass mg/kg-min	Fe Rel Rate/Area mg/m²-min	Zn Rel Rate/Area mg/m²-min
E5-1	Al Sheet	4.1	190	30	17.8	1.855	0.0021		37.2	3.6	1.9	0.0		
E5-2	Al Sheet	4.1	190	60	17.8				-31.7	0.4	0.7	0.0		
E5-3	Al Sheet	4.1	190	90	17.8				0.0	0.1	-0.9	0.0		
C5-1	Al Sheet	8	190	30	17.8	1.848	-0.0012		30.8	0.0	4.0	0.3		
C5-2	Al Sheet	8	190	60	17.8				48.2	0.0	-1.8	-0.2		
C5-3	Al Sheet	8	190	90	17.8				55.1	0.0	0.0	0.0		
Q7-1	Al Sheet	8	190	30	25.7	2.4662	0.0128		85.8	6.9	9.8	1.7		
Q7-2	Al Sheet	8	190	60	25.7				48.7	-1.6	1.9	-0.3		
Q7-3	Al Sheet	8	190	90	25.7				77.2	-0.6	-4.0	-0.1		
D5-1	Al Sheet	12	190	30	17.8	1.8569	0.2769		559.6	0.0	1.0	0.3		
D5-2	Al Sheet	12	190	60	17.8				189.0	0.0	3.1	0.1		
D5-3	Al Sheet	12	190	90	17.8				73.1	0.0	-1.7	-0.1		
K7-1	Al Sheet	4.1	265	30	25.7	2.595	0.0405		4.3					
K7-2	Al Sheet	4.1	265	60	25.7				3.3					
K7-3	Al Sheet	4.1	265	90	25.7				4.4					
N7-1	Al Sheet	8	265	30	25.7	1.8651	0.106		411.7	5.7	32.7	3.4		

Run	Material	pH_a	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m²-min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m²-min	Zn Rel Rate / Area mg/m²-min
N7-2	Al Sheet	8	265	60	25.7				348.7	-0.9	-5.7	-2.9		
N7-3	Al Sheet	8	265	90	25.7				235.6	-1.2	-2.3	0.0		
S7-1	Al Sheet	12	265	30	25.7	2.68	0.7884		17782.1					
S7-2	Al Sheet	12	265	60	25.7				11705.6					
S7-3	Al Sheet	12	265	90	25.7				-10824.1					
P4-1	Blank	4.1	190	30										
P4-2	Blank	4.1	190	60										
P4-3	Blank	4.1	190	90										
N4-1	Blank	12	265	30		0	1.2E-16							
N4-2	Blank	12	265	60										
N4-3	Blank	12	265	90										
B5-1	Calsil	4.1	190	30	4E+05	4.09	0.2025	0.96		144.5	138.4	31.6		
B5-2	Calsil	4.1	190	60				0.17		-12.5	2.4	-7.1		
B5-3	Calsil	4.1	190	90				-0.03		-0.9	-1.0	-2.3		
B6-1	Calsil	4.1	190	30		4.188	0.1733	1.36		111.3	113.0	16.0		
B6-2	Calsil	4.1	190	60				0.14		23.4	13.5	-4.7		
B6-3	Calsil	4.1	190	90				0.04		13.0	11.0	-0.3		
B7-1	Calsil	4.1	190	30		4.178	0.1471	1.00		98.9	94.0	24.9		
B7-2	Calsil	4.1	190	60				0.37		59.9	70.2	11.1		
B7-3	Calsil	4.1	190	90				-0.05		-1.1	-3.8	-6.3		
B8-1	Calsil	4.1	190	30		2.079	0.0985	1.87		165.3	152.8	19.5		
B8-2	Calsil	4.1	190	60				1.52		38.2	41.7	4.3		
B8-3	Calsil	4.1	190	90				0.08		25.7	18.7	-0.1		
E3-1	Calsil	4.1	190	30		4.185	0.1592	2.23		133.4	115.8	11.0		
E3-2	Calsil	4.1	190	60				0.48		-2.1	-6.1	-2.0		
E3-3	Calsil	4.1	190	90				-0.11		0.7	-3.3	-0.9		
C2-1	Calsil	8	190	30		4.181	0.0936	0.90		0.0	3.7	0.0		
C2-2	Calsil	8	190	60				-0.15		37.9	77.4	13.8		
C2-3	Calsil	8	190	90				-0.07		-6.1	-9.1	-4.3		
R7-1	Calsil	8	190	30		6.0604	-1.6229	1.47		19.5	162.1	25.4		
R7-2	Calsil	8	190	60				-0.50		1.5	24.5	-0.9		
R7-3	Calsil	8	190	90				0.00		0.7	18.7	0.0		
P8-1	Calsil	12	190	30		6.0599	-0.0423	3.57		5.8	204.8	11.3		
P8-2	Calsil	12	190	60				0.19		-1.1	-17.5	-3.5		
P8-3	Calsil	12	190	90				-2.35		0.9	-26.6	5.4		
K2-1	Calsil	4.1	265	30		6.0607	0.3808	0.50		23.9	68.7	9.4		
K2-2	Calsil	4.1	265	60				-0.02		6.7	8.3	-1.3		
K2-3	Calsil	4.1	265	90				0.02		0.5	-11.9	-2.3		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

								Al Rel Rate / Mass	Al Rel Rate / Area	Ca Rel Rate / Mass	Si Rel Rate / Mass	S Rel Rate / Mass	Fe Rel Rate / Area	Zn Rel Rate / Area
Run	Material	pHₐ	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	mg / kg-min	mg / m²-min	mg / kg-min	mg / kg-min	mg / kg-min	mg/m²-min	mg/m²-min
H2-1	Caksil	8	265	30		6.0604	0.2893	0.82		6.8	72.7	5.1		
H2-2	Caksil	8	265	60				-0.03		0.3	10.4	0.1		
H2-3	Caksil	8	265	90				0.00		0.5	2.8	-0.3		
L2-1	Caksil	8	265	30		6.0635	0.4751	0.40		8.6	51.7	5.4		
L2-2	Caksil	8	265	60				0.34		3.2	26.2	3.4		
L2-3	Caksil	8	265	90				-0.17		-3.2	-22.5	-3.6		
M2-1	Caksil	12	265	30		6.0603	-0.5981	1.11		1.2	158.7	20.2		
M2-2	Caksil	12	265	60				0.51		0.1	-2.5	-6.6		
M2-3	Caksil	12	265	90				1.17		0.1	-3.7	-4.0		
E8-1	Concrete	4.1	190	30	4E+05	4.009	0.1675	6.70		416.5	31.3	7.4		
E8-2	Concrete	4.1	190	60				-4.97		39.4	2.8	-0.3		
E8-3	Concrete	4.1	190	90				-0.23		47.3	-5.1	-0.6		
Q1-1	Concrete	4.1	190	30	5E+05	5.8005	1.0765	7.78		122.5	28.3	18.8		
Q1-2	Concrete	4.1	190	60				-1.18		-6.2	-5.1	-5.8		
Q1-3	Concrete	4.1	190	90				-0.91		-6.7	0.4	-2.3		
C8-1	Concrete	8	190	30		4.01		1.81		65.2	10.5	6.7		
C8-2	Concrete	8	190	60				-0.15		15.0	2.6	4.2		
C8-3	Concrete	8	190	90				-0.10		-0.3	-0.3	0.0		
R1-1	Concrete	8	190	30	5E+05	5.7998	0.3293	3.95		21.6	20.8	2.7		
R1-2	Concrete	8	190	60				-0.20		-0.6	-0.8	-0.2		
R1-3	Concrete	8	190	90				0.56		3.4	3.0	0.5		
D8-1	Concrete	12	190	30	4E+05	4.0515	0.2272	3.03		23.8	6.3	4.2		
D8-2	Concrete	12	190	60				1.20		8.2	1.8	2.1		
D8-3	Concrete	12	190	90				0.30		0.9	0.3	0.1		
K5-1	Concrete	4.1	265	30	5E+05	5.8013	0.2811	5.24		83.2	12.3	1.7		
K5-2	Concrete	4.1	265	60				-1.86		-13.6	0.1	-0.6		
K5-3	Concrete	4.1	265	90				-0.19		0.2	3.2	-0.1		
L5-1	Concrete	8	265	30	5E+05	5.7998	0.4084	8.63		43.6	15.5	3.8		
L5-2	Concrete	8	265	60				1.61		6.3	2.8	0.3		
L5-3	Concrete	8	265	90				-0.48		-1.6	-0.2	-0.1		
M5-1	Concrete	12	265	30	5E+05	5.799	0.6977	31.95		30.9	34.3	22.2		
M5-2	Concrete	12	265	60				-1.46		1.1	-2.8	-0.4		
M5-3	Concrete	12	265	90				-8.96		7.1	3.4	0.4		
B3-1	Durablanket	4.1	190	30		0.412	-0.0032	4.20		0.0	2.1	0.0		
B3-2	Durablanket	4.1	190	60				0.29		0.0	1.6	0.0		
B3-3	Durablanket	4.1	190	90				-0.07		0.0	0.0	0.0		
E2-1	Durablanket	4.1	190	30		0.413	0.0131	1.26		18.3	10.6	0.1		
E2-2	Durablanket	4.1	190	60				-1.05		-0.7	-0.7	-0.1		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m²- min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m²- min	Zn Rel Rate / Area mg/m²- min

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m²- min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m²- min	Zn Rel Rate / Area mg/m²- min
E2-3	Durablanket	4.1	190	90				0.22		-1.3	-0.5	0.0		
C3-1	Durablanket	8	190	30		0.411	-3.7581	24.47		0.0	37.5	0.0		
C3-2	Durablanket	8	190	60				26.55		0.0	42.3	0.0		
C3-3	Durablanket	8	190	90				7.05		0.0	15.0	0.0		
Q4-1	Durablanket	8	190	30		0.5943	0.008	8.16		10.8	20.1	2.4		
Q4-2	Durablanket	8	190	60				0.55		-1.4	-7.2	0.6		
Q4-3	Durablanket	8	190	90				1.47		0.6	4.0	-0.8		
R4-1	Durablanket	8	190	30		0.5941	0.0013	19.51		36.7	68.6	6.5		
R4-2	Durablanket	8	190	60				11.31		5.3	-19.4	-0.2		
R4-3	Durablanket	8	190	90				-3.94		-5.7	-6.6	-1.2		
D3-1	Durablanket	12	190	30		0.41	-0.0395	41.32		0.0	91.7	0.6		
D3-2	Durablanket	12	190	60				107.74		0.0	271.7	2.2		
D3-3	Durablanket	12	190	90				40.74		0.0	103.7	-0.4		
K1-1	Durablanket	4.1	265	30		0.5937	0.0084	17.15		-43.7	-54.9	0.0		
K1-2	Durablanket	4.1	265	60				-2.90		-7.6	-11.9	0.0		
K1-3	Durablanket	4.1	265	90				-1.57		-13.5	-14.5	0.0		
O4-1	Durablanket	4.1	265	30		0.5948	-0.0011	21.21		20.0	74.2	0.0		
O4-2	Durablanket	4.1	265	60				4.06		-6.8	-2.0	0.0		
O4-3	Durablanket	4.1	265	90				5.54		-2.4	12.3	0.0		
L1-1	Durablanket	8	265	30		0.5943	0.0273	50.91		8.3	62.1	0.0		
L1-2	Durablanket	8	265	60				51.77		0.5	71.5	0.0		
L1-3	Durablanket	8	265	90				59.99		2.1	77.8	0.2		
M1-1	Durablanket	12	265	30		0.5942	0.0798	232.45		3.8	307.4	1.5		
M1-2	Durablanket	12	265	60				-54.92		-0.8	-81.8	1.0		
M1-3	Durablanket	12	265	90				103.25		0.5	271.8	0.0		
E6-1	Fiberglass	4.1	190	30		0.905	-0.0125	-1.18		19.0	25.3	10.1		
E6-2	Fiberglass	4.1	190	60				-1.07		-7.7	-19.2	-4.5		
E6-3	Fiberglass	4.1	190	90				0.00		3.2	1.0	-0.1		
Q3-1	Fiberglass	4.1	190	30		1.3001	0.0137	3.29		7.8	15.7	20.1		
Q3-2	Fiberglass	4.1	190	60				-0.22		-0.2	1.3	-3.5		
Q3-3	Fiberglass	4.1	190	90				0.44		0.9	3.0	-1.5		
C6-1	Fiberglass	8	190	30		0.901	0.0023	3.02		-1.3	26.3	14.6		
C6-2	Fiberglass	8	190	60				0.29		1.2	26.0	0.5		
C6-3	Fiberglass	8	190	90				0.51		-2.9	26.6	0.4		
R3-1	Fiberglass	8	190	30		1.3007	0.0147	11.14		16.0	37.6	23.4		
R3-2	Fiberglass	8	190	60				-0.39		3.2	29.3	0.4		
R3-3	Fiberglass	8	190	90				-0.23		0.3	22.3	-3.4		
D6-1	Fiberglass	12	190	30		0.899	0.0497	10.97		29.4	320.3	11.1		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg/kg-min	Al Rel Rate / Area mg/m²-min	Ca Rel Rate / Mass mg/kg-min	Si Rel Rate / Mass mg/kg-min	S Rel Rate / Mass mg/kg-min	Fe Rel Rate / Area mg/m²-min	Zn Rel Rate / Area mg/m²-min
D6-2	Fiberglass	12	190	60				5.30		39.3	351.8	1.2		
D6-3	Fiberglass	12	190	90				2.50		21.0	182.0	1.4		
K4-1	Fiberglass	4.1	265	30		1.3	0.0613	13.01		28.5	105.5	3.7		
K4-2	Fiberglass	4.1	265	60				-4.85		14.1	112.2	-1.7		
K4-3	Fiberglass	4.1	265	90				-1.63		12.5	80.1	-0.3		
L4-1	Fiberglass	8	265	30		1.2997	0.0534	8.22		14.6	129.4	8.2		
L4-2	Fiberglass	8	265	60				1.49		8.9	50.2	-0.5		
L4-3	Fiberglass	8	265	90				1.14		6.8	53.7	-0.2		
M4-1	Fiberglass	12	265	30		1.2998	0.1882	23.87		34.6	612.4	21.0		
M4-2	Fiberglass	12	265	60				5.06		12.4	138.6	-4.2		
M4-3	Fiberglass	12	265	90				0.91		-17.6	21.3	-2.3		
P2-1	Galvanized	4.1	190	30	91.2	13.9354	0.0114							1.3
P2-2	Galvanized	4.1	190	60	91.2									0.7
P2-3	Galvanized	4.1	190	90	91.2									0.6
Q6-1	Galvanized	8	190	30	91.2	14.0768	0.0083							0.0
Q6-2	Galvanized	8	190	60	91.2									0.0
Q6-3	Galvanized	8	190	90	91.2									0.0
P6-1	Galvanized	12	190	30	91.2	14.2719	0.0013							1.0
P6-2	Galvanized	12	190	60	91.2									0.3
P6-3	Galvanized	12	190	90	91.2									0.4
O2-1	Galvanized	4.1	265	30	91.2	13.8539	0.0077							0.5
O2-2	Galvanized	4.1	265	60	91.2									0.5
O2-3	Galvanized	4.1	265	90	91.2									-0.8
N6-1	Galvanized	8	265	30	91.2	14.0797	0.0006							0.0
N6-2	Galvanized	8	265	60	91.2									0.0
N6-3	Galvanized	8	265	90	91.2									0.0
N2-1	Galvanized	12	265	30	91.2	14.1467	0.0045							3.8
N2-2	Galvanized	12	265	60	91.2									2.5
N2-3	Galvanized	12	265	90	91.2									1.1
P3-1	Interam	4.1	190	30		0.0394	-0.002	63.99		99.0	0.0	0.0		
P3-2	Interam	4.1	190	60				3.99		-35.1	0.0	0.0		
P3-3	Interam	4.1	190	90				-1.29		1.4	0.0	0.0		
Q8-1	Interam	8	190	30		0.0389	0.0087	1074.9		833.5	1076.6	123.5		
Q8-2	Interam	8	190	60				292.30		-401.1	-214.8	-25.4		
Q8-3	Interam	8	190	90				-307.21		42.1	-153.4	-3.1		
P7-1	Interam	12	190	30		0.039	0.0287	17396.6		339.0	2405.9	64.5		
P7-2	Interam	12	190	60				-9348.8		-11.6	-476.3	31.2		
P7-3	Interam	12	190	90				1762.23		-40.3	-400.1	-37.5		

Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m²-min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m²-min	Zn Rel Rate / Area mg/m²-min
O3-1	Interam	4.1	265	30		0.0392	-0.0002	130.78		173.1	519.0	0.0		
O3-2	Interam	4.1	265	60				1.64		-54.9	-104.6	0.0		
O3-3	Interam	4.1	265	90				22.48		-3.6	27.1	0.0		
N8-1	Interam	8	265	30		0.039	0.0082	696.40		370.0	656.4	67.8		
N8-2	Interam	8	265	60				526.90		-2.2	86.1	-5.4		
N8-3	Interam	8	265	90				187.46		-39.2	-89.2	-12.7		
N3-1	Interam	12	265	30		0.0391	0.0243	4567.2		56.1	2121.5	40.6		
N3-2	Interam	12	265	60				1709.4		6.0	747.1	11.6		
N3-3	Interam	12	265	90				-10.95		8.0	-43.8	28.5		
B4-1	Mineral Wool	4.1	190	30		0.639	0.0198	3.88		0.0	3.6	0.0		
B4-2	Mineral Wool	4.1	190	60				0.10		0.0	1.3	0.0		
B4-3	Mineral Wool	4.1	190	90				-0.06		0.0	0.0	0.0		
E4-1	Mineral Wool	4.1	190	30		0.641	0.0172	0.00		36.7	15.6	0.0		
E4-2	Mineral Wool	4.1	190	60				0.00		-22.1	-8.0	0.0		
E4-3	Mineral Wool	4.1	190	90				0.00		-1.8	-0.9	0.0		
C4-1	Mineral Wool	8	190	30		0.641	0.0018	3.37		0.0	10.2	0.6		
C4-2	Mineral Wool	8	190	60				0.50		0.0	4.3	-0.2		
C4-3	Mineral Wool	8	190	90				0.97		0.0	7.1	0.1		
R6-1	Mineral Wool	8	190	30		0.9292	0.0097	19.36		45.2	36.7	10.0		
R6-2	Mineral Wool	8	190	60				3.58		4.8	12.3	0.4		
R6-3	Mineral Wool	8	190	90				-1.82		-3.8	-3.0	-1.8		
D4-1	Mineral Wool	12	190	30		0.64	0.0065	12.82		18.1	70.7	1.5		
D4-2	Mineral Wool	12	190	60				16.26		37.3	111.6	1.1		
D4-3	Mineral Wool	12	190	90				10.20		42.3	67.5	0.6		
K3-1	Mineral Wool	4.1	265	30		0.9288	0.052	6.45		21.1	22.0	0.0		
K3-2	Mineral Wool	4.1	265	60				-0.87		8.8	3.8	0.0		
K3-3	Mineral Wool	4.1	265	90				3.37		20.9	15.0	0.0		
H4-1	Mineral Wool	8	265	30		0.9301	0.0548	13.68		17.4	48.5	0.0		
H4-2	Mineral Wool	8	265	60				10.04		14.7	35.2	0.0		
H4-3	Mineral Wool	8	265	90				0.71		3.0	3.0	0.0		
L3-1	Mineral Wool	8	265	30		0.9298	0.0312	22.46		63.9	80.1	0.0		
L3-2	Mineral Wool	8	265	60				2.26		11.3	9.8	0.0		
L3-3	Mineral Wool	8	265	90				-2.62		-6.9	-10.3	0.0		
M3-1	Mineral Wool	12	265	30		0.9288	0.0923	25.41		9.6	305.0	3.8		
M3-2	Mineral Wool	12	265	60				34.72		63.9	51.7	0.5		
M3-3	Mineral Wool	12	265	90				-5.88		-3.0	-20.0	-1.1		
E7-1	Min-K	4.1	190	30		0.0255	0.0075	0.00		253.2	432.9	0.0		
E7-2	Min-K	4.1	190	60				0.00		-6.8	-241.5	0.0		

Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	Al Rel Rate / Mass mg / kg-min	Al Rel Rate / Area mg / m²- min	Ca Rel Rate / Mass mg / kg-min	Si Rel Rate / Mass mg / kg-min	S Rel Rate / Mass mg / kg-min	Fe Rel Rate / Area mg/m²- min	Zn Rel Rate / Area mg/m²- min
E7-3	Min-K	4.1	190	90				0.00		-25.2	117.4	0.0		
Q2-1	MIN-K	4.1	190	30		0.0372	0.0188	112.51		215.9	1581.7	30.9		
Q2-2	MIN-K	4.1	190	60				-5.68		-71.8	-229.3	9.5		
Q2-3	MIN-K	4.1	190	90				19.39		43.7	-131.5	2.2		
C7-1	Min-K	8	190	30		0.0259	0.0064	79.05		24.3	5682.5	40.6		
C7-2	Min-K	8	190	60				-0.66		18.6	3858.2	-6.5		
C7-3	Min-K	8	190	90				-0.91		0.0	1446.7	-1.7		
R2-1	MIN-K	8	190	30		0.0374	0.0091	202.92		478.0	10343.0	64.6		
R2-2	MIN-K	8	190	60				-3.29		-81.8	5411.1	-11.3		
R2-3	MIN-K	8	190	90				60.01		196.2	4681.4	42.8		
D7-1	Min-K	12	190	30		0.0258	0.0078	130.48		0.0	13560.0	88.6		
D7-2	Min-K	12	190	60				-1.64		0.0	2633.0	12.2		
D7-3	Min-K	12	190	90				7.24		0.0	2022.5	16.6		
K8-1	Min-K	4.1	265	30		0.0373	0.0135	936.31		446.0	4272.9	9.0		
K8-2	Min-K	4.1	265	60				-510.38		-181.9	203.5	-8.0		
K8-3	Min-K	4.1	265	90				-192.67		-15.6	1625.6	0.0		
L8-1	Min-K	8	265	30		0.0374	0.0169	132.33		290.8	4581.2	0.0		
L8-2	Min-K	8	265	60				178.57		34.7	2722.3	0.0		
L8-3	Min-K	8	265	90				-84.96		-36.0	-2225.0	0.0		
M8-1	MIN-K	12	265	30		0.0373	0.0241	198.93		87.3	14823.8	52.4		
M8-2	Min-K	12	265	60				577.16		24.1	-1360.5	2.0		
M8-3	Min-K	12	265	90				686.15		57.6	-1688.7	6.2		
B1-1	Nukon	4.1	190	30		0.898	0.0091	2.56		0.0	3.6	8.1		
B1-2	Nukon	4.1	190	60				0.00		0.0	2.0	3.8		
B1-3	Nukon	4.1	190	90				0.06		0.0	3.5	2.3		
E1-1	Nukon	4.1	190	30		0.9	0.0177	1.10		14.6	13.5	7.1		
E1-2	Nukon	4.1	190	60				-0.40		-2.2	-1.1	0.1		
E1-3	Nukon	4.1	190	90				-0.49		-0.3	-0.3	-1.1		
C1-1	Nukon	8	190	30		0.905	0.0139	2.27		0.0	19.7	6.1		
C1-2	Nukon	8	190	60				-0.29		0.0	-12.1	-4.8		
C1-3	Nukon	8	190	90				0.78		0.0	34.6	3.3		
R5-1	Nukon	8	190	30		1.3002	0.036	11.79		27.8	67.4	20.0		
R5-2	Nukon	8	190	60				18.85		1.1	22.0	-1.4		
R5-2	Nukon	8	190	90				-14.05		1.4	29.1	-0.6		
D1-1	Nukon	12	190	30		0.909	0.0452	3.71		0.0	47.9	1.8		
D1-2	Nukon	12	190	60				-0.14		0.0	-9.7	-1.6		
D1-3	Nukon	12	190	90				-0.31		0.0	-13.4	0.0		
K6-1	Nukon	4.1	265	30		1.2997	0.0744	8.44		22.2	70.0	0.0		

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

								Al Rel Rate / Mass	Al Rel Rate / Area	Ca Rel Rate / Mass	Si Rel Rate / Mass	S Rel Rate / Mass	Fe Rel Rate / Area	Zn Rel Rate / Area
Run	Material	pH$_a$	T °F	Time min	Surf. Area cm²	Mat. Start Mass g	Mass Loss g	mg / kg-min	mg / m²-min	mg / kg-min	mg / kg-min	mg / kg-min	mg/m²-min	mg/m²-min
K6-2	Nukon	4.1	265	60				-4.30		3.4	7.7	0.0		
K6-3	Nukon	4.1	265	90				0.18		4.8	32.0	0.0		
L6-1	Nukon	8	265	30		1.3007	0.0784	9.14		28.0	167.8	4.2		
L6-2	Nukon	8	265	60				2.91		26.9	51.2	-0.6		
L6-3	Nukon	8	265	90				0.21		-16.7	2.5	-0.9		
M6-1	Nukon	12	265	30		1.3012	0.1428	37.33		59.2	764.1	16.2		
M6-2	Nukon	12	265	60				-9.96		-18.2	-203.6	-6.8		
M6-3	Nukon	12	265	90				3.06		-5.6	136.5	-2.3		
P1-1	Steel	4.1	190	30	35	5.5708	-0.004						2.8	
P1-2	Steel	4.1	190	60	35								8.6	
P1-3	Steel	4.1	190	90	35								10.8	
Q5-1	Steel	8	190	30	35	11.1945	0.0019						0.0	
Q5-2	Steel	8	190	60	35								0.0	
Q5-3	Steel	8	190	90	35								0.0	
P5-1	Steel	12	190	30	35	5.1959	-0.0013						0.2	
P5-2	Steel	12	190	60	35								-0.1	
P5-3	Steel	12	190	90	35								0.1	
O1-1	Steel	4.1	265	30	35	5.0217	0.003						0.4	
O1-2	Steel	4.1	265	60	35								3.7	
O1-3	Steel	4.1	265	90	35								1.4	
N5-1	Steel	8	265	30	35	6.3007	0.0012						0.0	
N5-2	Steel	8	265	60	35								0.0	
N5-3	Steel	8	265	90	35								1.3	
N1-1	Steel	12	265	30	35	5.7289	-0.001						0.8	
N1-2	Steel	12	265	60	35								0.1	
N1-3	Steel	12	265	90	35								0.0	

Table A-2: Test Matrix, Material Areas, Material Mass, and Release Rates

APPENDIX B: HIGH MAGNIFICATION SEM OF PRECIPITATES

SEM analyses were performed on the thirteen precipitates formed during bench testing in order to estimate the size of each precipitate's constituent particles. The high magnification pictures are attached below.

Figure B-1: High Magnification SEM of PPT1
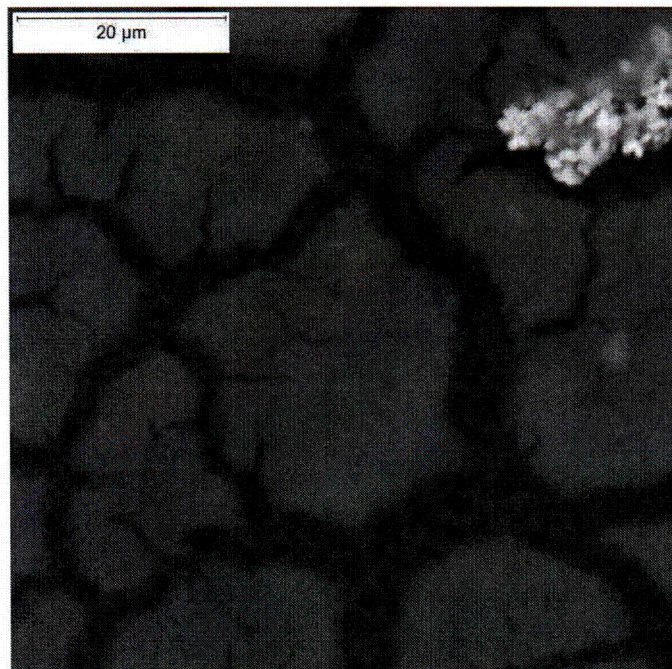
Figure B-2: High Magnification SEM of PPT2
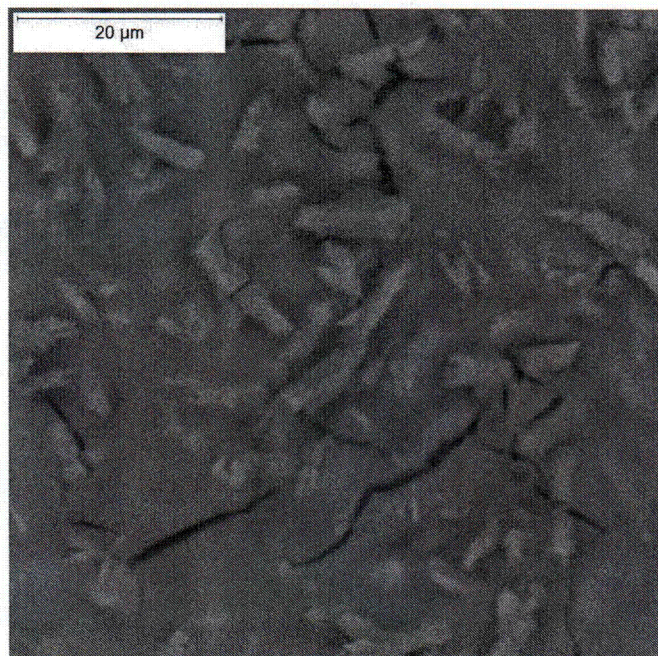
Figure B-3: High Magnification SEM of PPT3
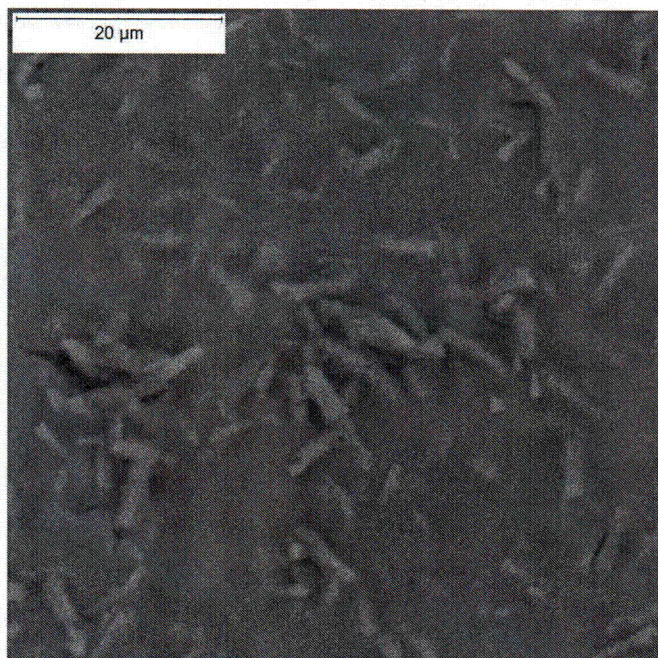
Figure B-4: High Magnification SEM of PPT12
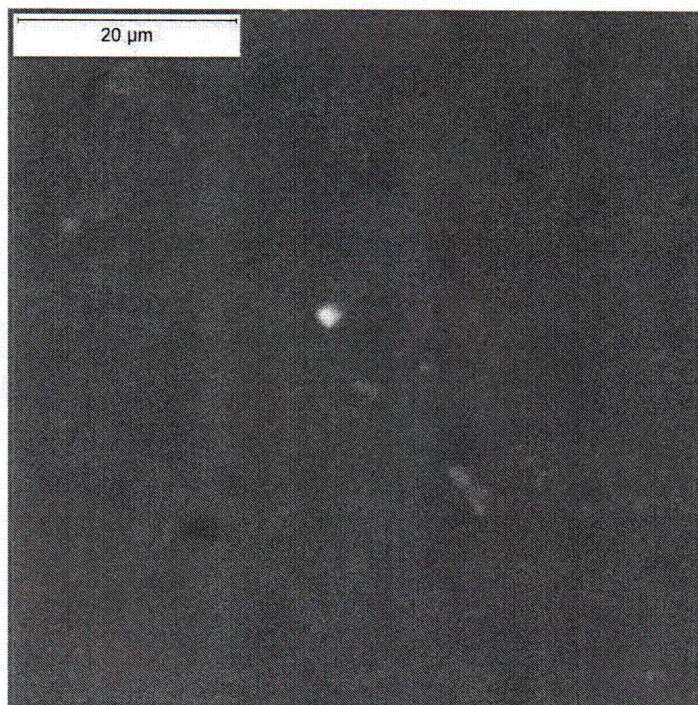
Figure B-5: High Magnification SEM of PPT13
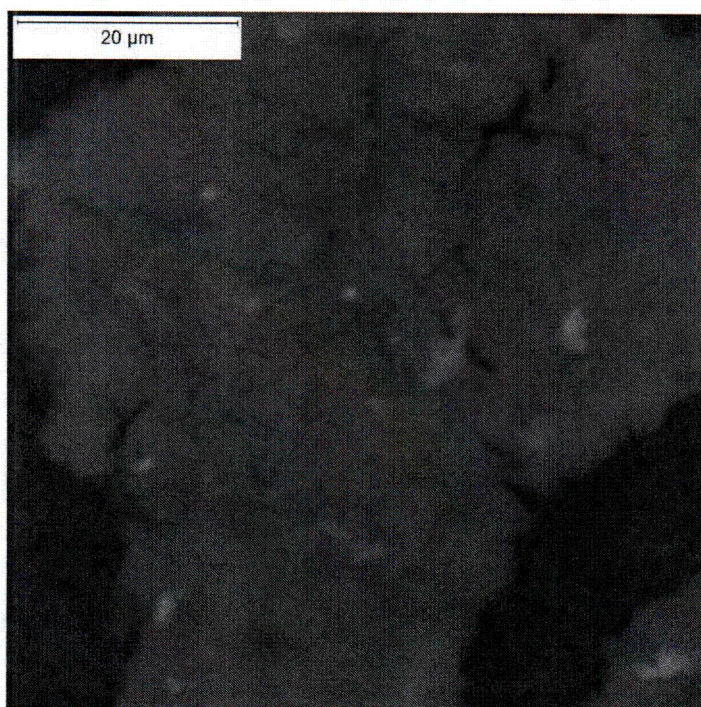
Figure B-6: High Magnification SEM of PPT14
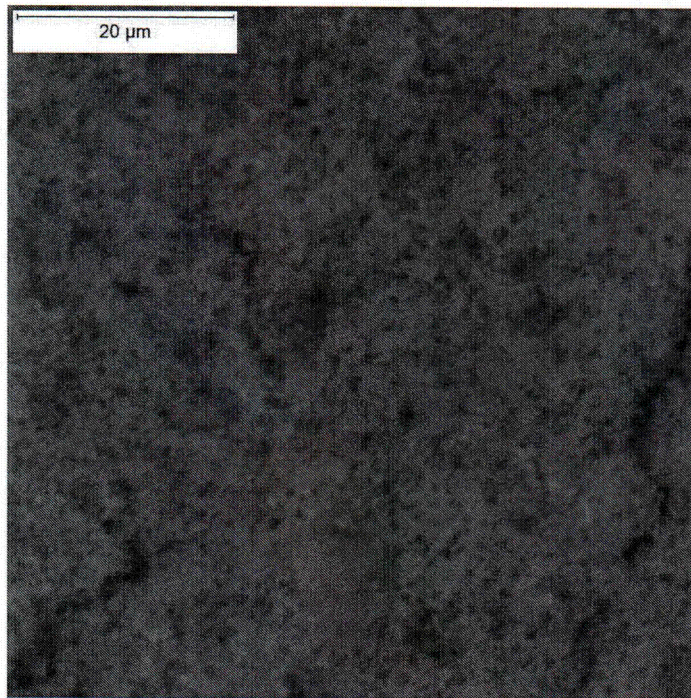
Figure B-7: High Magnification SEM of PPT16
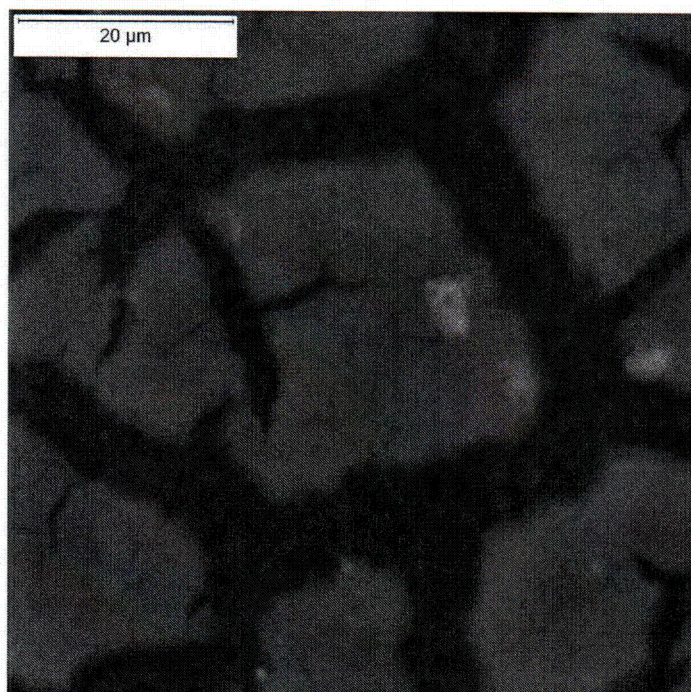
Figure B-8: High Magnification SEM of PPT22
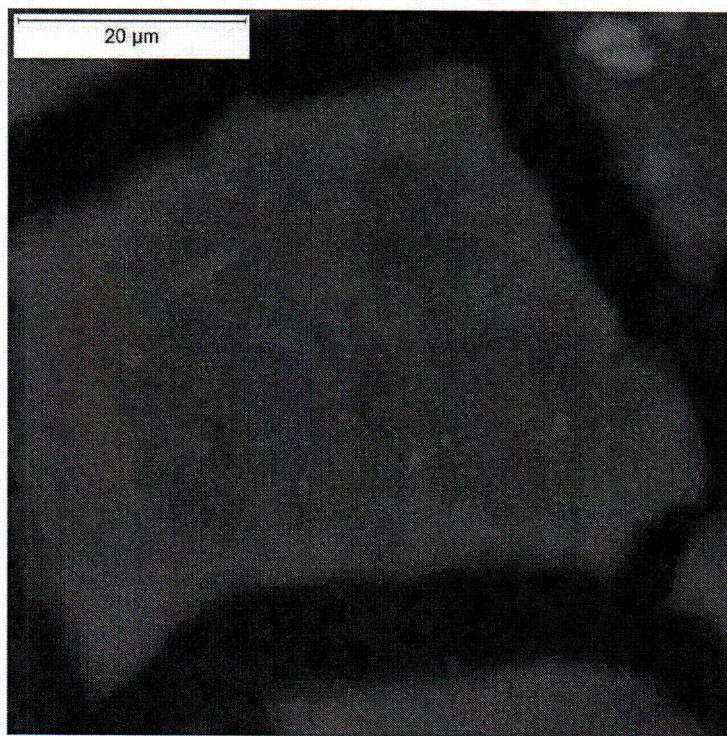
Figure B-9: High Magnification SEM of PPT24
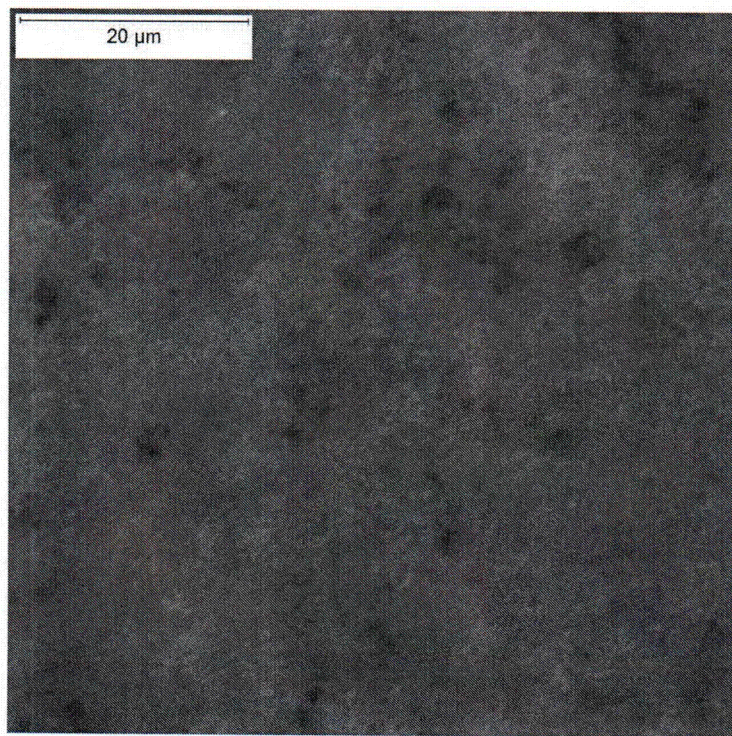
Figure B-10: High Magnification SEM of PPT30
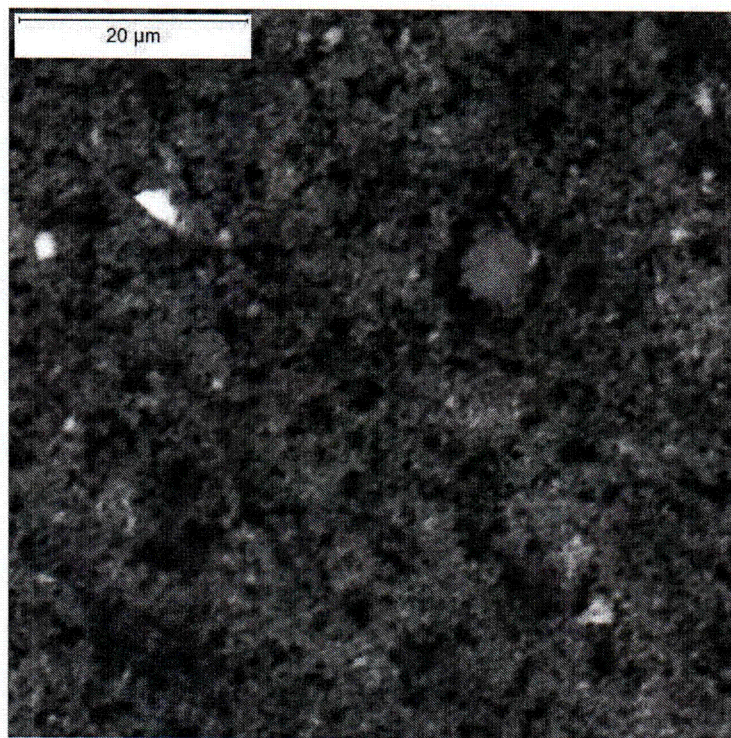
Figure B-11: High Magnification SEM of PPT35
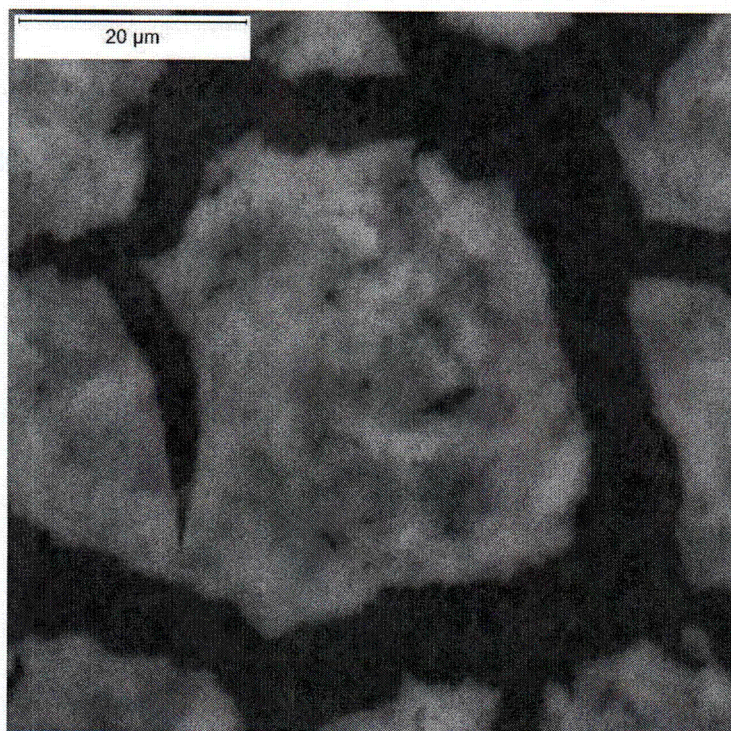
Figure B-12: High Magnification SEM of PPT38
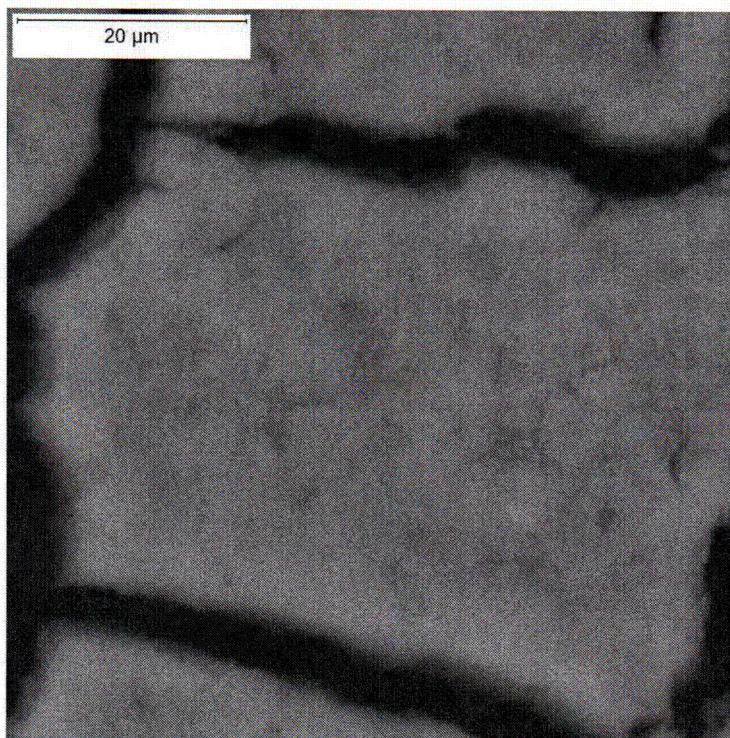
Figure B-13: High Magnification SEM of PPT60
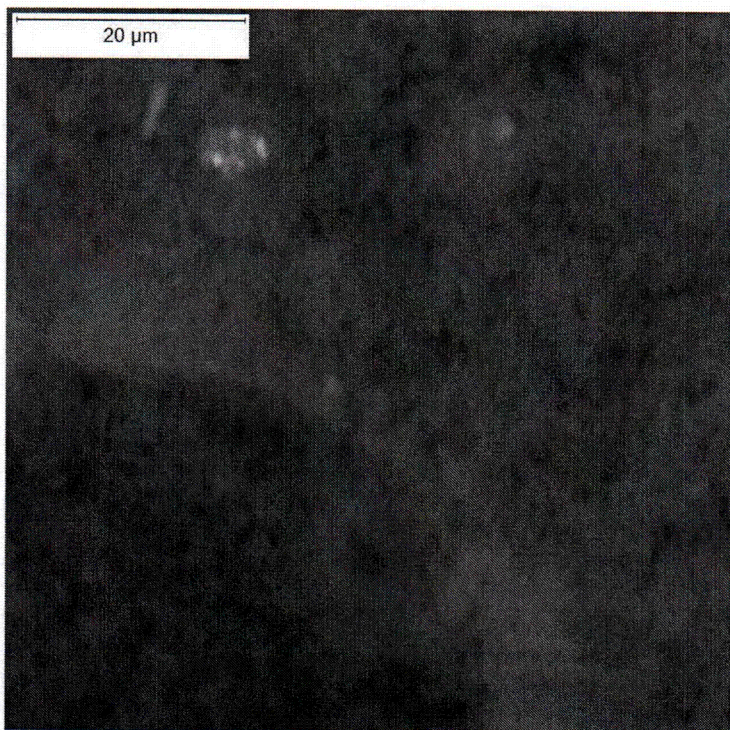
APPENDIX C: FILTERABILITY TEST DATA

The figures attached below contain the pressure drop versus flow rate data from the filterability tests performed on the precipitates produced during bench testing. A figure has been generated for each precipitate formed either by cooling or by chemical reaction due to pH adjustment or material combinations. Table C-1 summarizes the filter coefficient results calculated from this data in Section 5.3.

Table C-1: Summary of Filter K_f Results

PPT Run	Mass of PPT Filtered (g)	Method of Precipitation Formation	Slope of filtration curve (psi-min/ml)	Area (ft²)	Temp. (F)	K_f	K_{fx}	Viscosity (cP)	Temp. Corrected K_{fs}
1	0.0001	PPT on cooling, Concrete, pH 4	-0.0005	0.004	77.9	-26376	-0.106	0.8737	1387
2	0.0408	PPT on cooling, Concrete, pH 8	0.3891	0.004	76.7	36	0.818	0.8937	1419
3	0.0362	PPT on cooling, Mineral Wool, pH 4	-0.0992	0.004	75	-145	-2.578	0.9142	1451
12	0.0012	PPT on cooling, FiberFax, pH 4	0.0568	0.004	76	249	0.195	0.8937	1419
13	0.0005	PPT on cooling, FiberFax, pH 12	0.0293	0.004	77	481	0.196	0.8937	1419
14	0.0048	PPT on cooling, FiberFax, pH 12	0.0106	0.004	77	1336	59.451	0.8937	1419
16	-0.0001	PPT on cooling, FiberFax, pH 12	0.0132	0.004	77	1068	-0.233	0.8937	1419
22	0.0003	PPT on cooling, FiberFax, pH 12	0.0263	0.004	78	524	0.136	0.8737	1387
24a	0.0048	PPT on cooling, Galvanized, pH 12	0.0342	0.004	71.1	442	1.621	0.9579	1520
24b	0.0048	PPT of Phosphates, CalSil	0.0450	0.004	75.7	321	1.069	0.9142	1451
24c	0.0048	PPT of Phosphates, Concrete	0.0674	0.004	74.8	214	0.653	0.9142	1451
24d	0.0048	pH 12 265 Fiberglass with pH 4 CalSil	0.0484	0.004	77.1	291	0.953	0.8937	1419
30	0.0005	PPT on cooling, Concrete, pH 4	0.0114	0.004	77.7	1205	2.483	0.8737	1387
35	0.0021	PPT on cooling, Concrete, pH 8	0.0294	0.004	78	469	0.803	0.8737	1387
38	0.0041	PPT on cooling, Mineral Wool, pH 4	1.082	0.004	78	13	0.028	0.8737	1387
60	0.0011	PPT on cooling, FiberFax, pH 4	0.0303	0.004	78	455	0.401	0.8737	1387
blank filter	--	--	0.00995	0.004	72.6	1485	--	0.9358	1485

Figure C-1 – dP vs. Flow for a Blank Filter @ 72.6°F (15 to 60 ml/min only)

(n = .9358 cP; zs = 0.009948537+/-0.000206245 psi-min/ml)
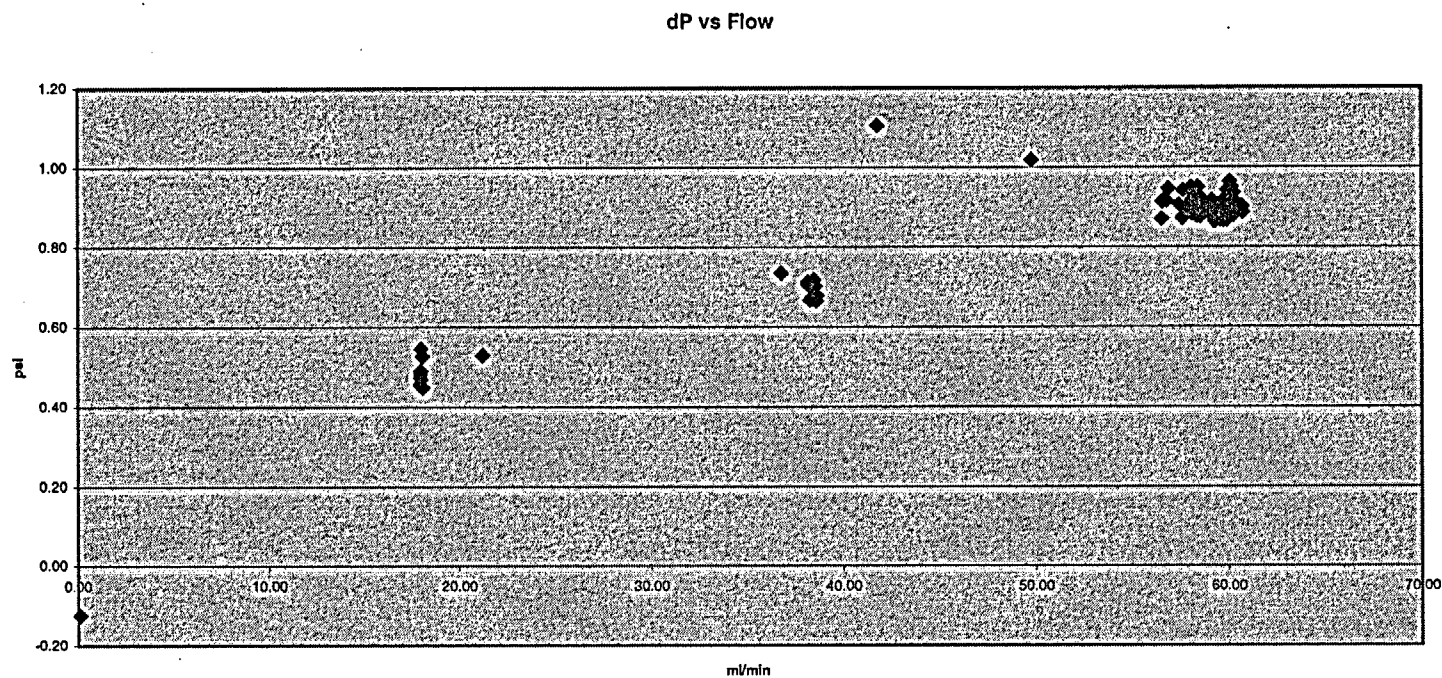
dP vs Flow

Figure C-2 – dP vs. Flow for PPT 24a @ 71.1°F

(n = .9579 cP; z = 0.034195272 +/- 0.00125012 psi-min/ml)
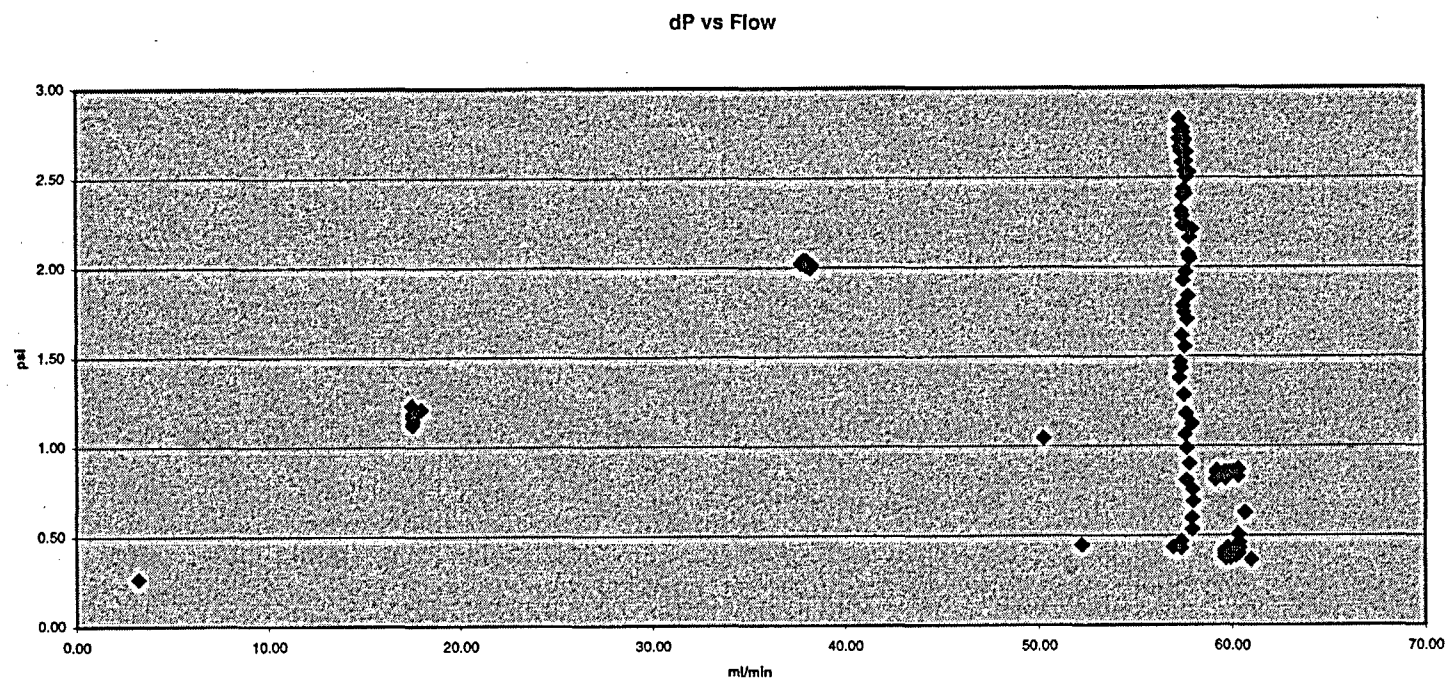
dP vs Flow

Figure C-3 – dP vs. Flow for PPT 24b @ 75.7°F

(n = .9142 cP; z = 0.045015726+/- 0.000439639 psi-min/ml)
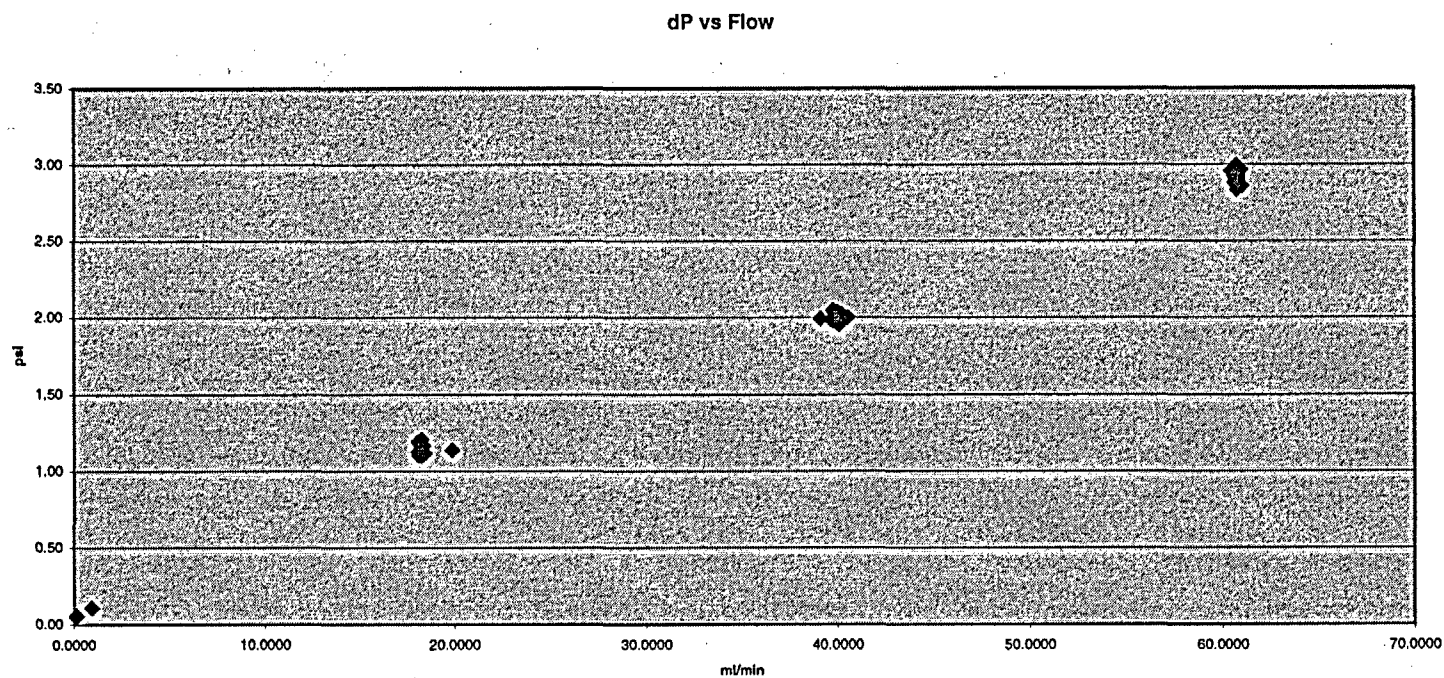
dP vs Flow

Figure C-4 – dP vs. Flow for PPT 24c @ 74.8°F

(n = .9142 cP; z = 0.067356571+/- 0.000738347 psi-min/ml)
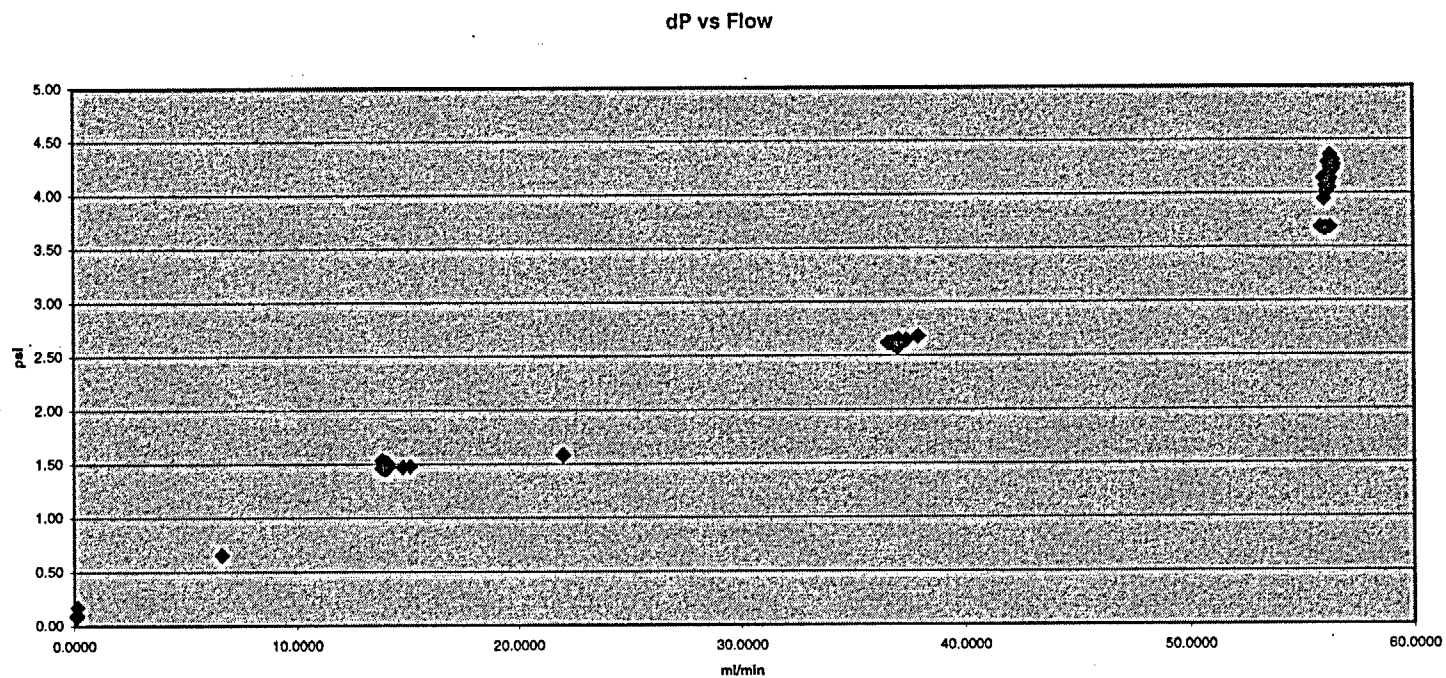
dP vs Flow

Figure C-5 – dP vs. Flow for PPT 24d @ 77.1°F

(n = .8937 cP; z = 0.048421822+/- 0.00103711 psi-min/ml)
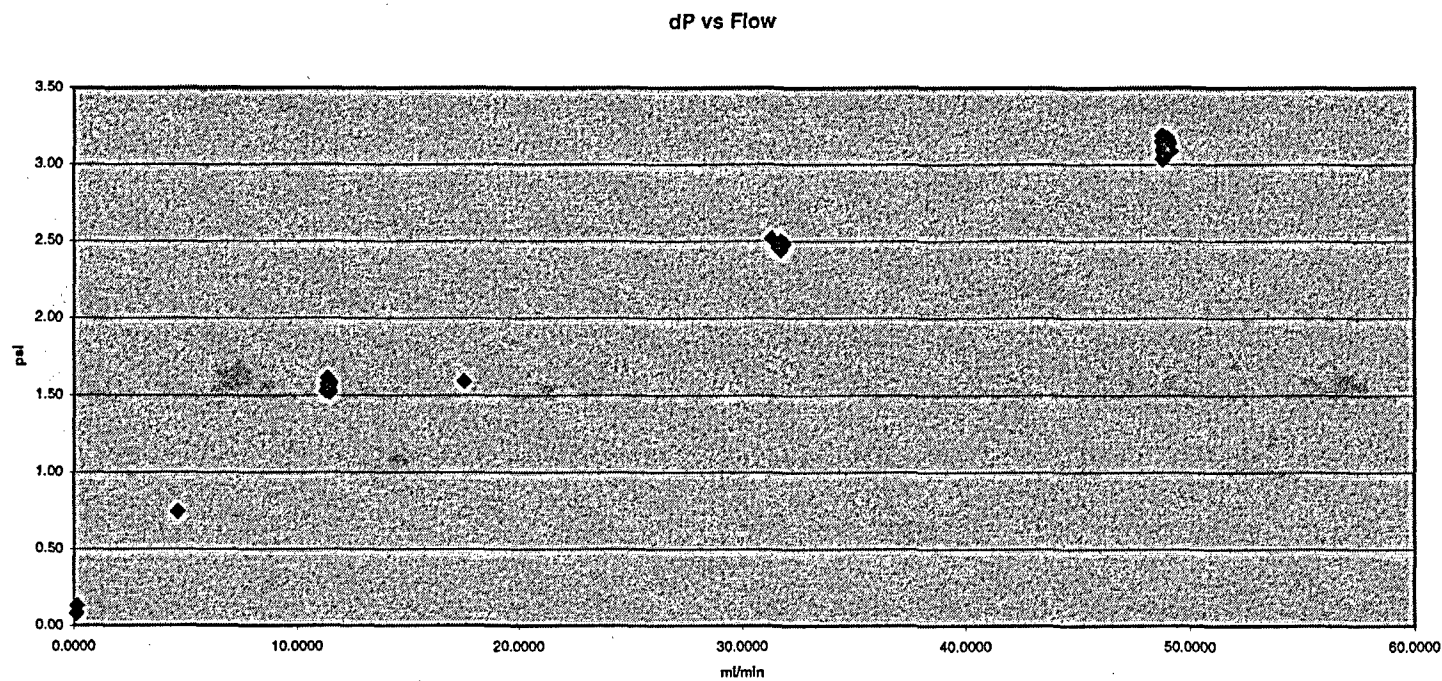
dP vs Flow

Figure C-6 – dP vs. Flow for PPT 1 @ 77.8°F

(n = .8737 cP; z = -0.000523053+/- 0.000184422 psi-min/ml)
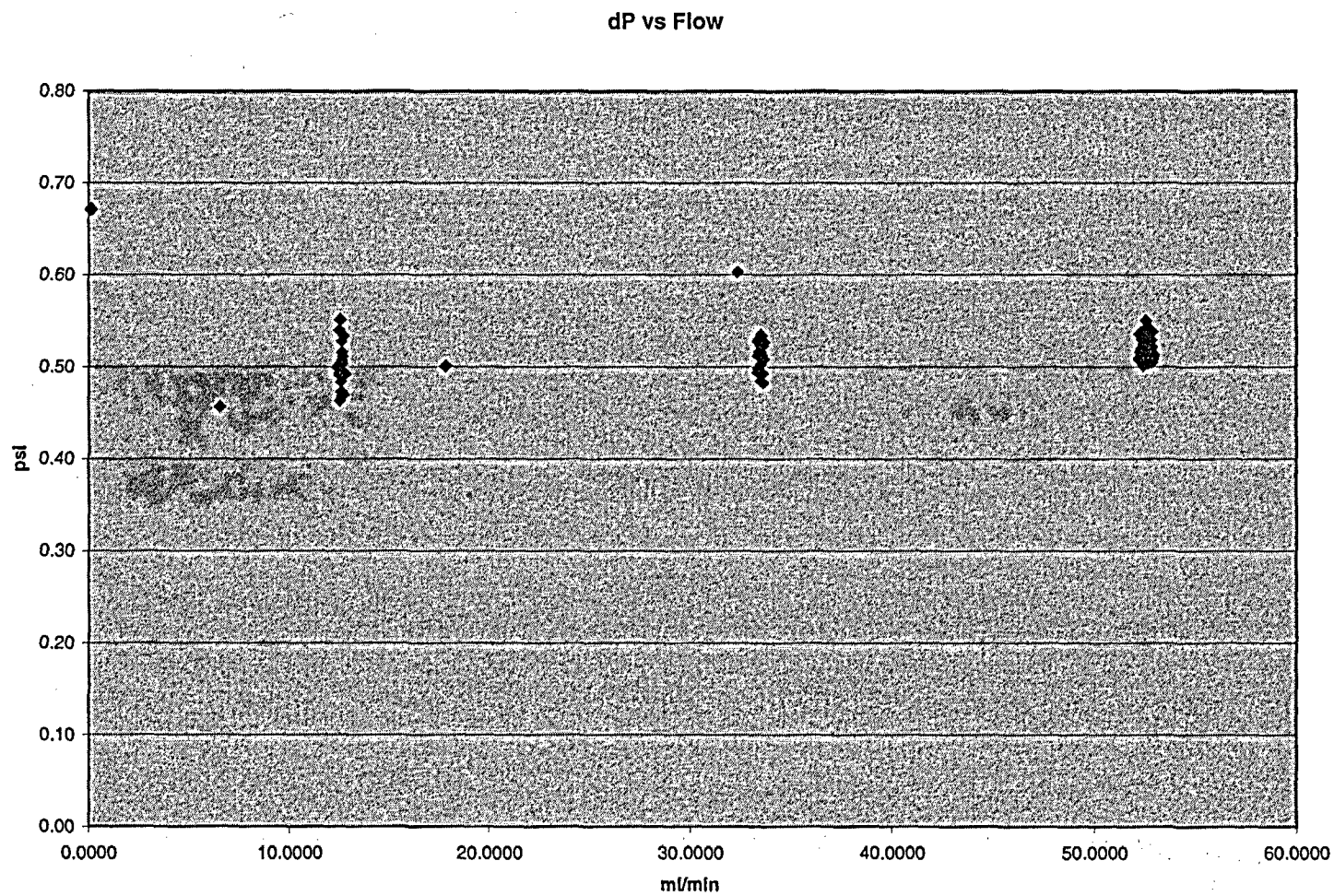
dP vs Flow

Figure C-7 – dP vs. Flow for PPT2 @ 77.8°F

(n = .8937 cP; z = 0.389122659+/- 0.00238118 psi-min/ml)
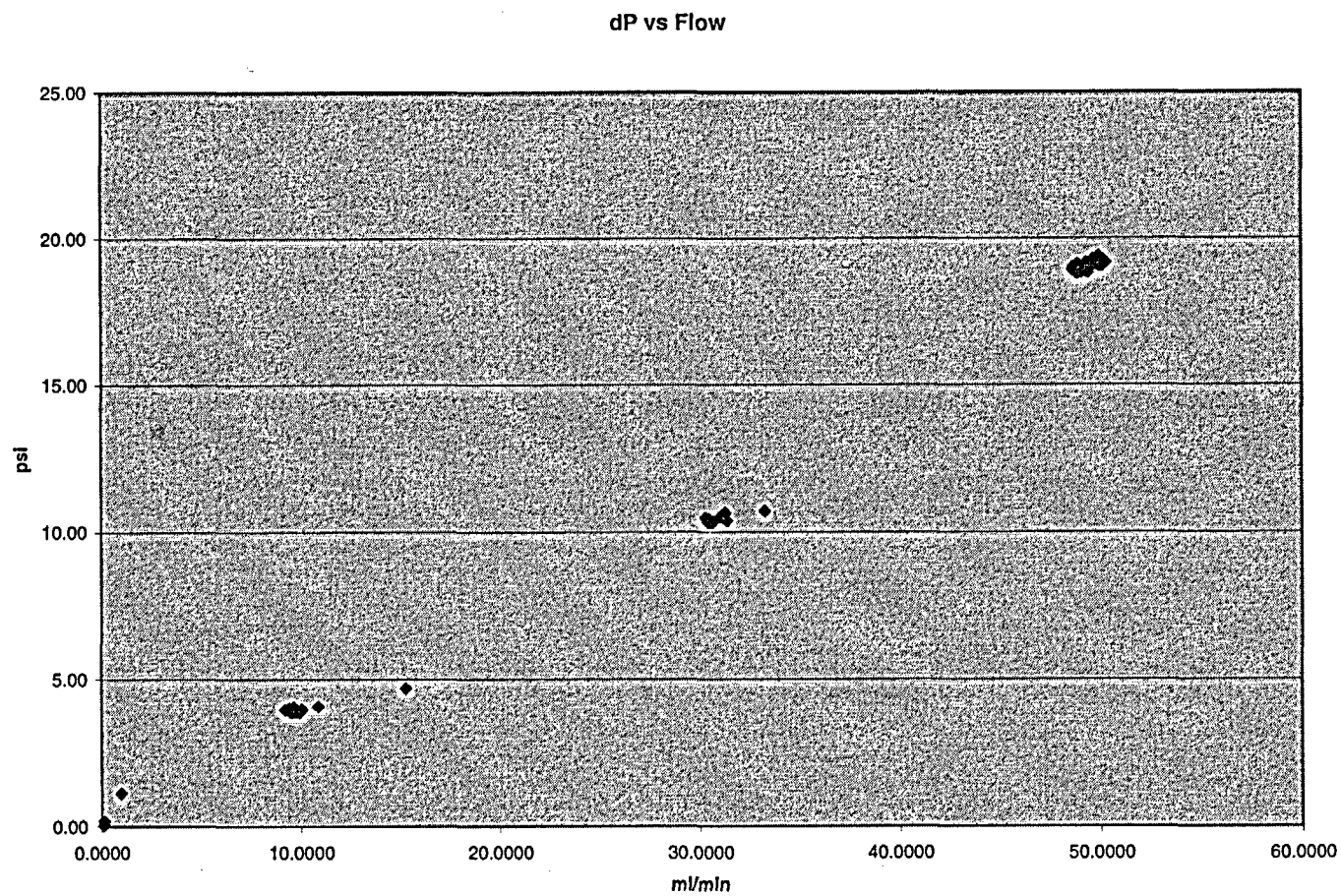
dP vs Flow

Figure C-8 – dP vs. Flow for PPT3 @ 67°F (7 to 48 ml/min only)

(n = 1.005 cP; z = 0.06320968+/-0.006169918 psi-min/ml)
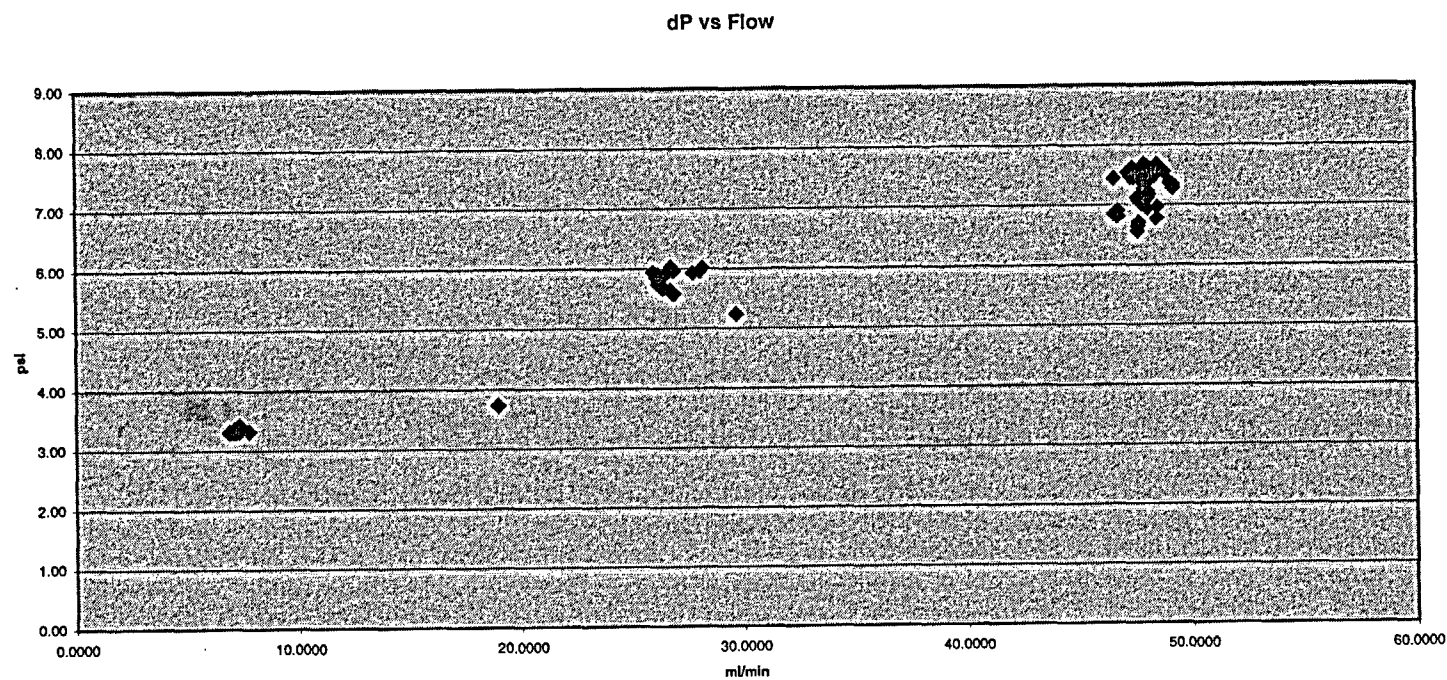
dP vs Flow

Figure C-9 – dP vs. Flow for PPT12 @ 76°F

(n = .8937 cP; z = 0.056765318+/- 0.000979488psi-min/ml)
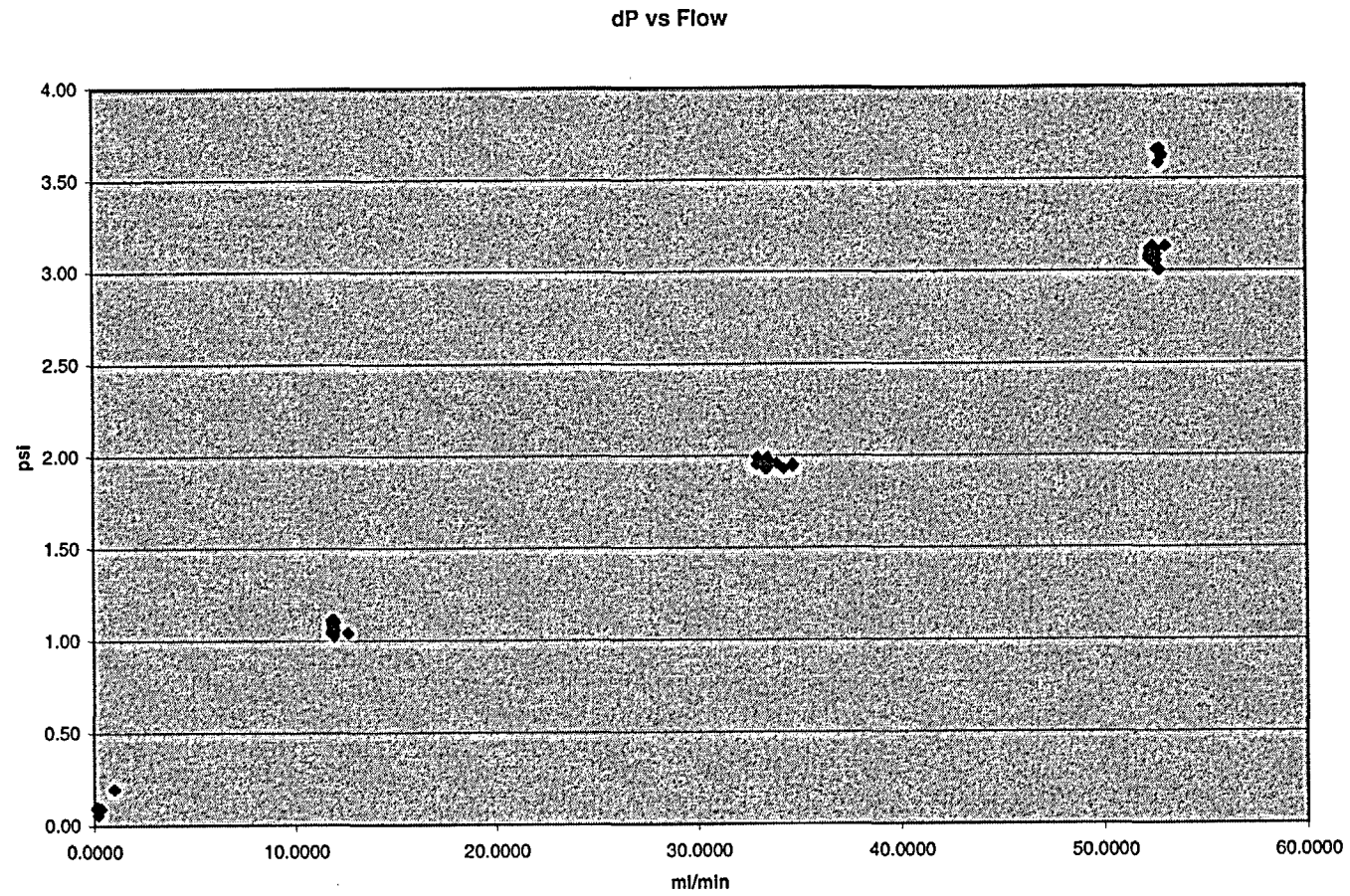
dP vs Flow

Figure C-10 – dP vs. Flow for PPT13 @ 77°F (0 to 13 ml/min only)

(n = .8937 cP; z = 0.029311817+/- 0.001103119 psi-min/ml)
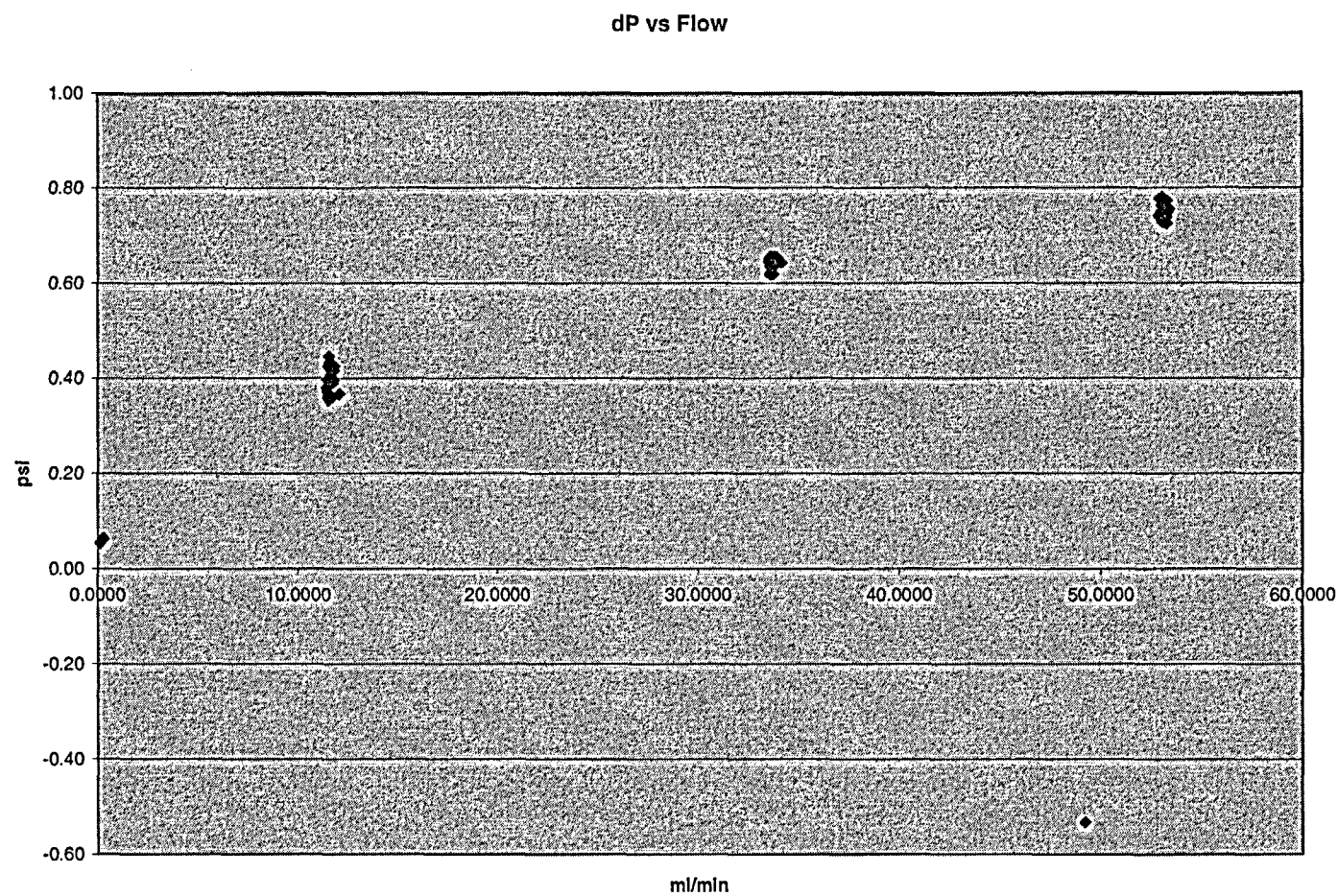
dP vs Flow

Figure C-11 – dP vs. Flow for PPT14 @ 77°F (0 to 33 ml/min only)

(n = .8937 cP; z = 0.010562088+/-0.000318675 psi-min/ml)
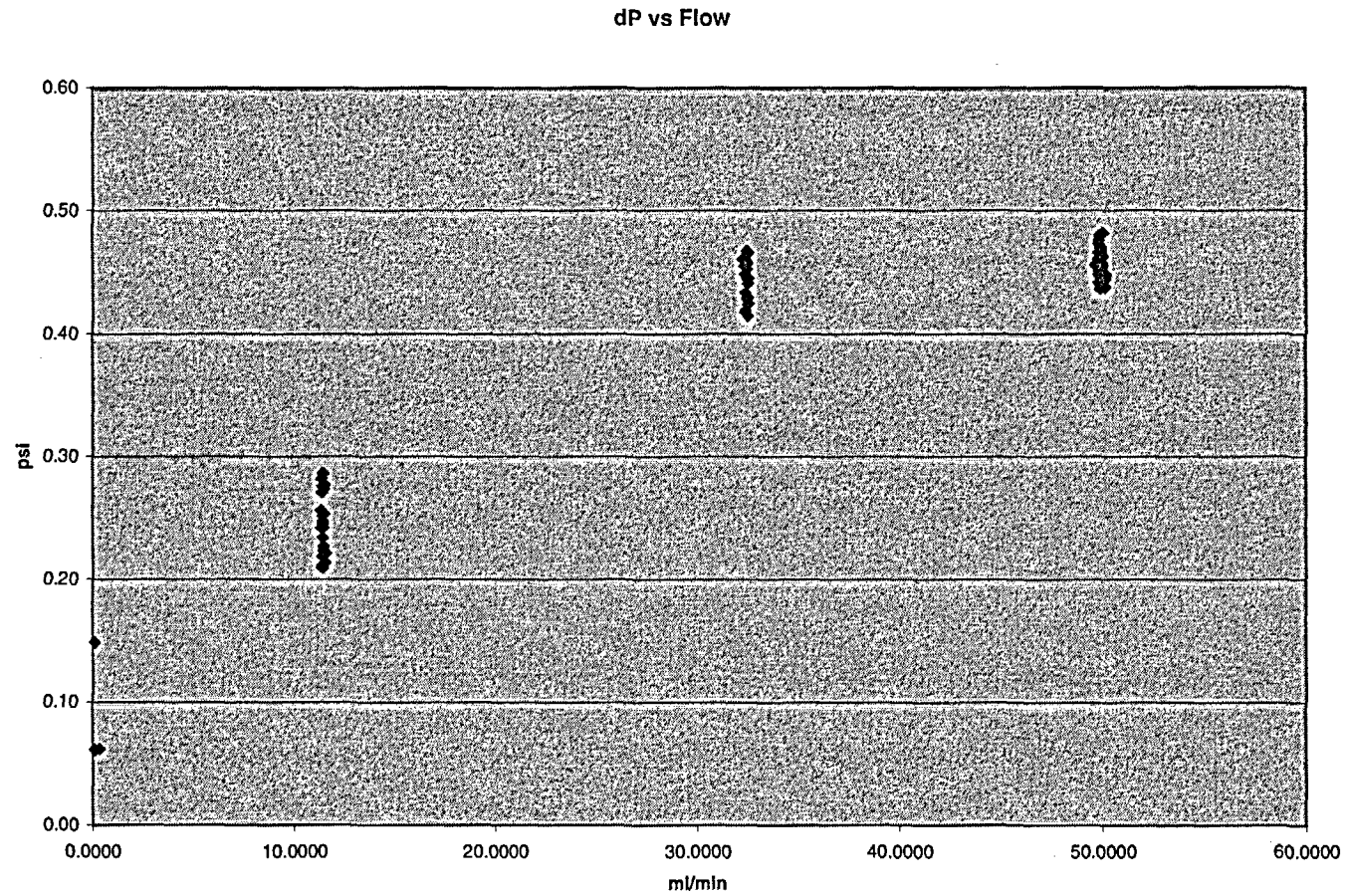
dP vs Flow

Figure C-12 – dP vs. Flow for PPT16 @ 78°F (0 to 30 ml/min only)

(n = .8737 cP; z = 0.013211422+/- 0.000471689 psi-min/ml)
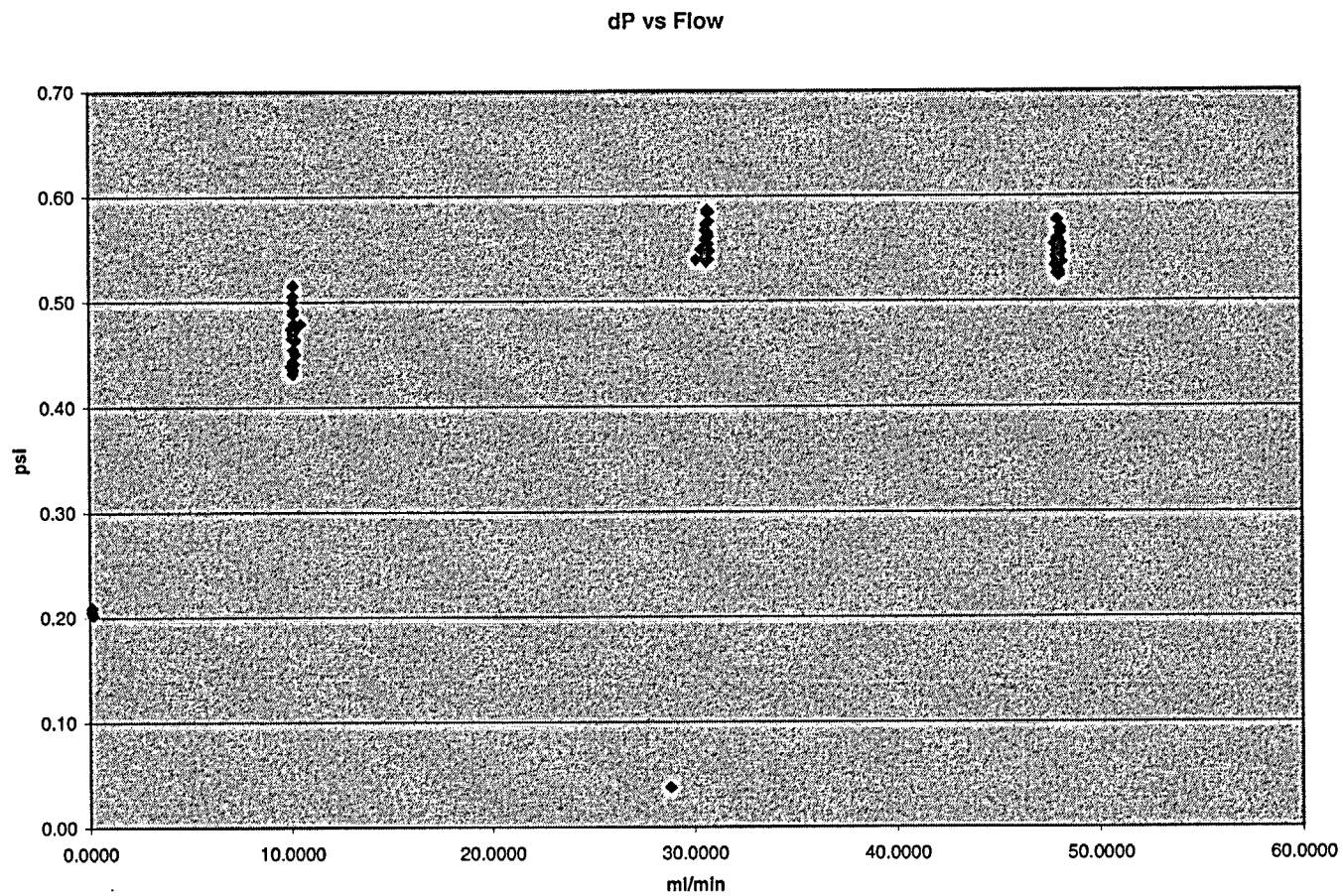
dP vs Flow

Figure C-13 – dP vs. Flow for PPT22 @ 78°F (0 to 10 ml/min only)

(n = .8737 cP; z = 0.026327465+/- 0.000526035 psi-min/ml)
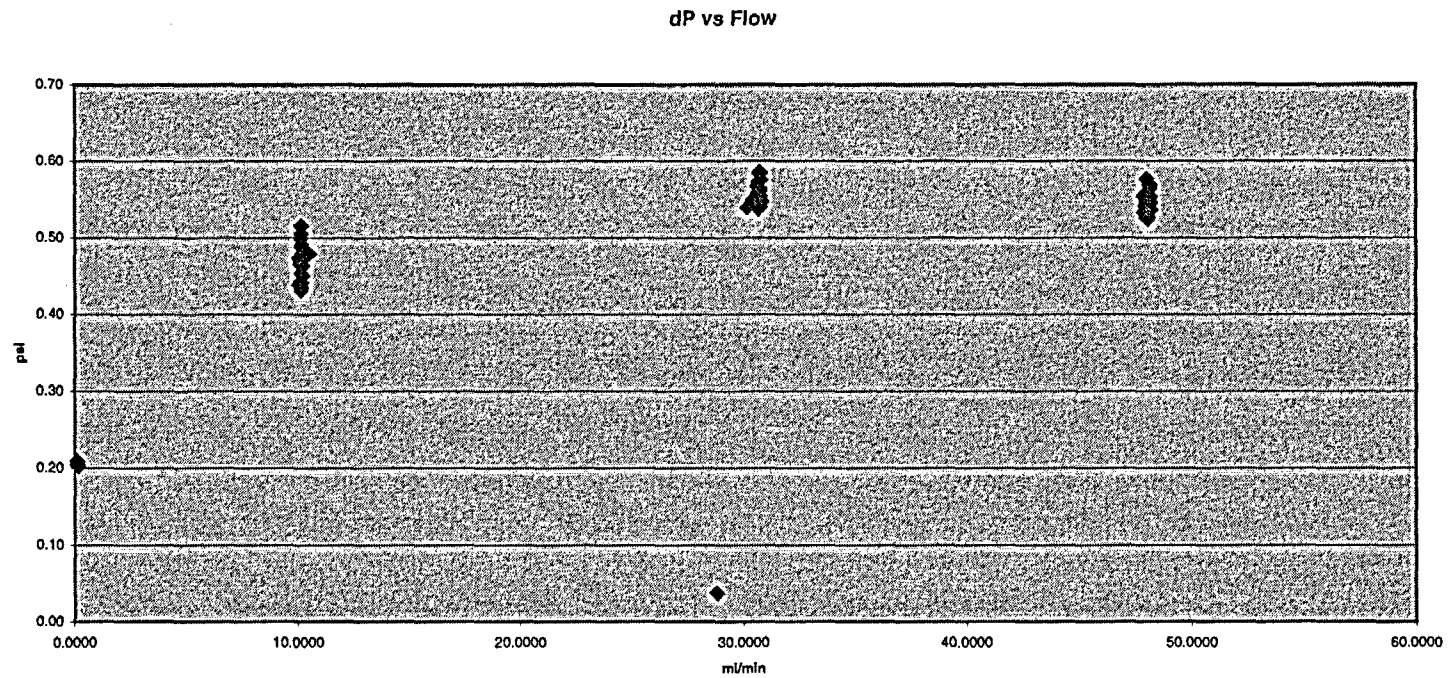
dP vs Flow

Figure C-14 – dP vs. Flow for PPT30 @ 77.7°F (0 to 35 ml/min only)

(n = .8737 cP; z = 0.011444646+/- 0.001024822 psi-min/ml
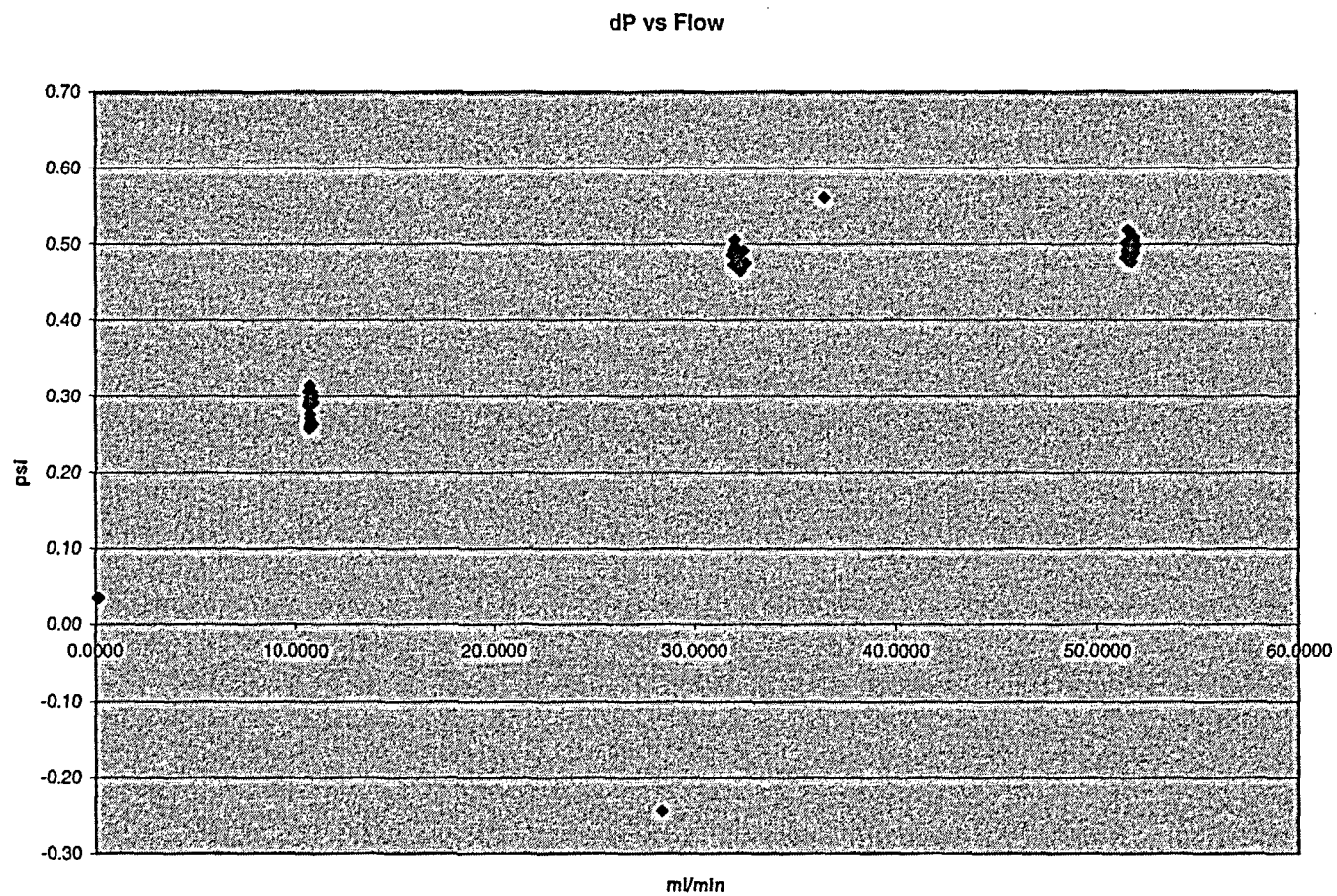
dP vs Flow

ml/min

Figure C-15 – dP vs. Flow for PPT35 @ 78°F (12 to 55 ml/min only)

(n = .8737 cP; z = 0.029387816+/- 0.00106635 psi-min/ml
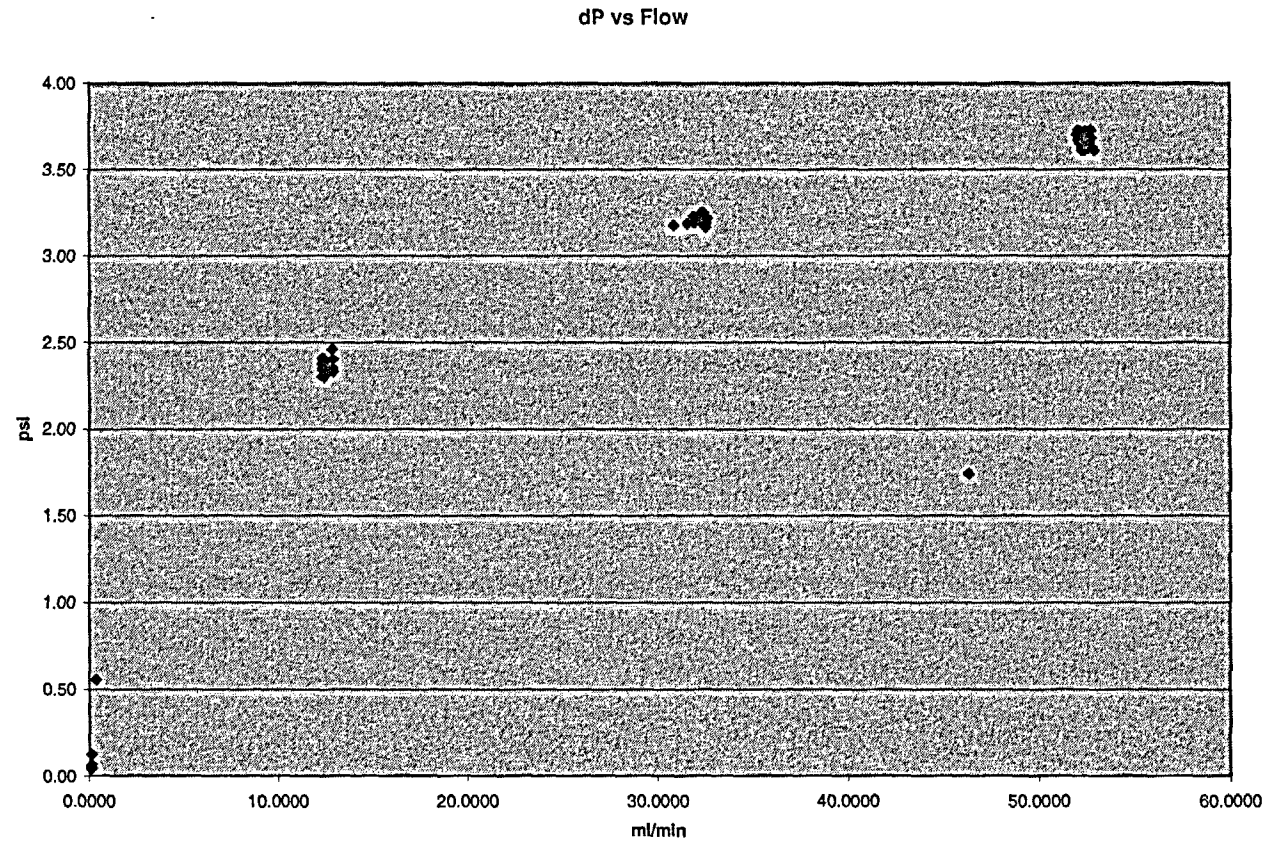
dP vs Flow

Figure C-16 – dP vs. Flow for PPT38 @ 78°F (0 to 24 ml/min only)

(n = .8737 cP; z = 1.082233604+/- 0.039970312 psi-min/ml)
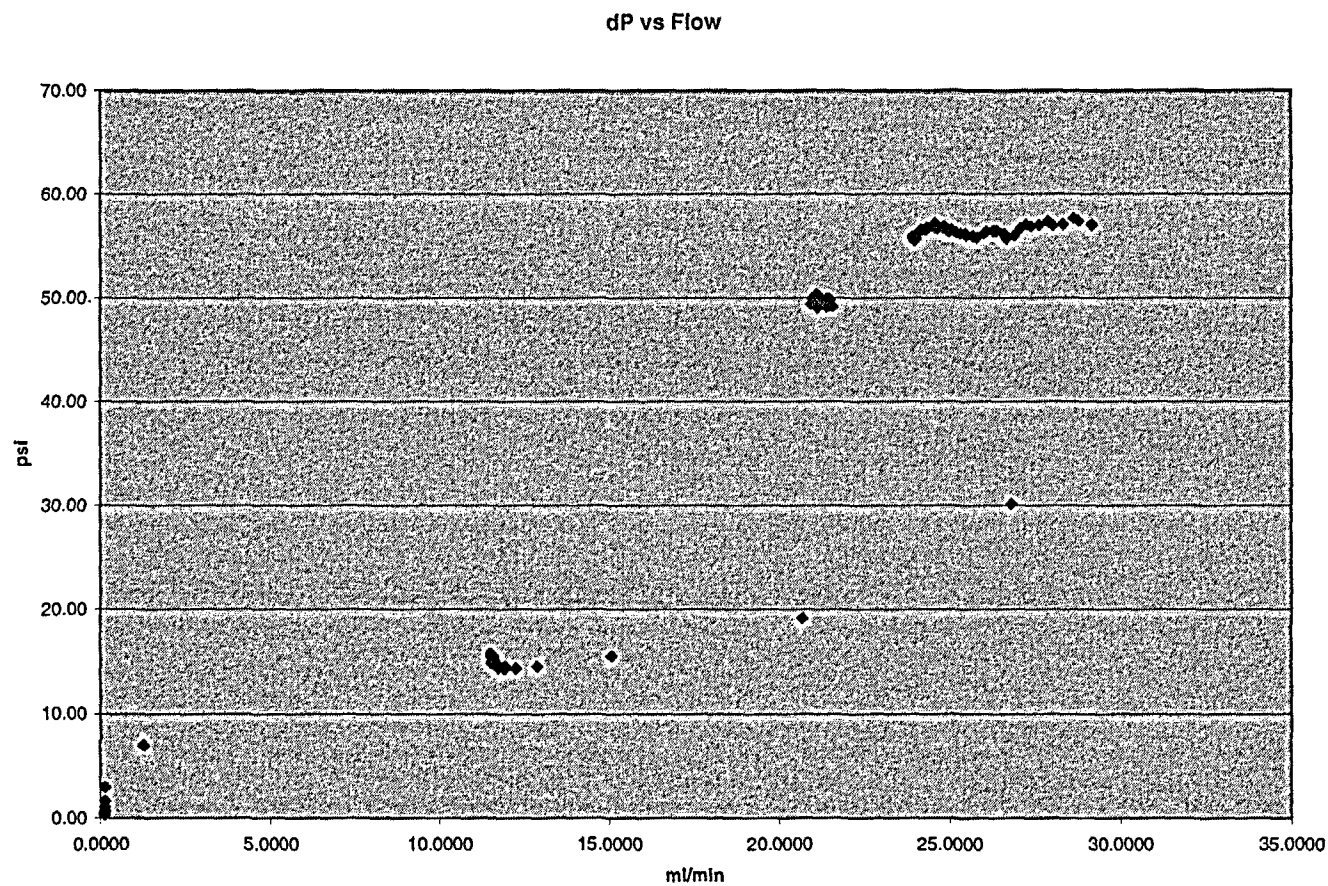
dP vs Flow

Figure C-17 – dP vs. Flow for PPT60 @ 78°F (15 to 48 ml/min only)

(n = .8737 cP; z = 0.030318299+/- 0.001161737 psi-min/ml

dP vs Flow
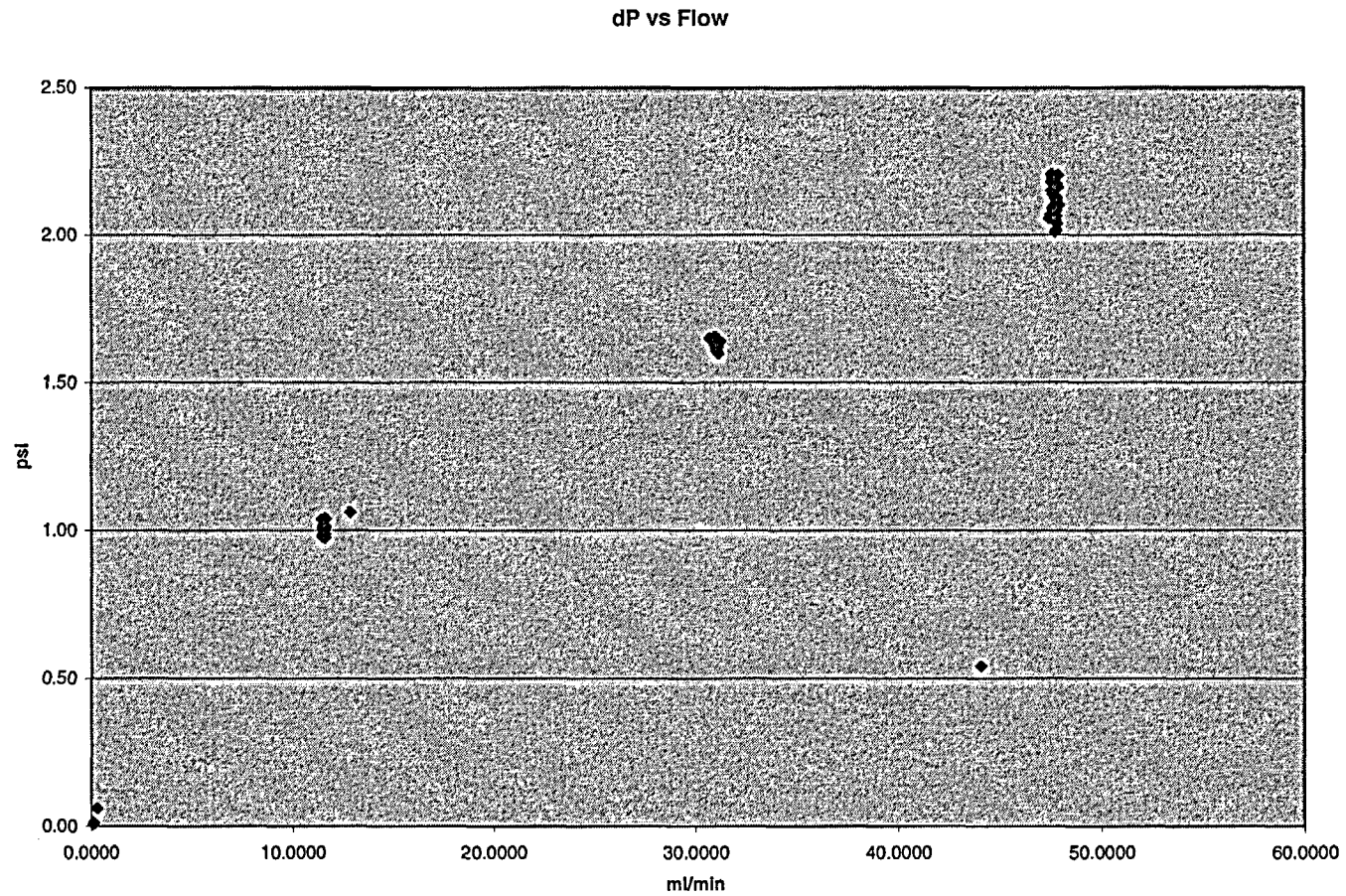
APPENDIX D: DETAILS OF CHEMICAL MODEL

This appendix presents the evaluations preformed in the Microsoft Excel file containing the chemical model developed as part of this test program, which is transmitted along with this report. The detailed calculations are provided for validation purposes and to meet internal QA requirements.

Worksheet = Time Temp pH Input

This worksheet is used to enter the time-temperature profiles, including sump and steam temperature, and time-pH profile in containment post-accident.

Column A contains the time in seconds from accident initiation to 30 days over 35 rows. Each row of Column B converts the Column A time to minutes by dividing each row entry by 60 sec/min, while Column C then converts to hours by dividing by 60 min/hr. Finally, Column D converts the time to days by dividing by 24 hr/day.

Columns E and F contain the sump pH and sump temperature values, respectively, at the corresponding times in Columns A-D. Similarly, Columns H and I contain the data for the spray pH and steam temperature.

Column G presents the option to allow the elemental mass already released into the sump solution to impact the dissolution rate from each material containing that element. In order to take credit for this effect on the dissolution rate, the sump solution must be mixed; this is indicated by entering 1 into the rows starting at the time the sump solution is assumed to become mixed.

Note that if data is entered over a different range of cells than is shown in the example, the worksheets referencing this data must all be changed by adding or subtracting rows accordingly. The easiest approach at this time is to adjust the data to fit into example cell range.

Worksheet = Materials Input

This worksheet is used to input the containment material data, such as that requested on the plant survey, and the recirculation water volume. The materials are divided into the material classes determined for testing. Also, there is a flag to indicate whether or not trisodium phosphate is used as a buffering agent.

Column A lists the material classes developed to sort the containment materials by chemical composition. Column B lists the materials within each class. Finally, the amount of each material should be input in Column C using the units listed in Column B. No calculations are performed in this worksheet.

Worksheet = Materials Conversions

This worksheet converts the material amounts input in the previous worksheet to mass for all materials but the aluminum. The mass input in the "Materials Input" worksheet is applied in this worksheet for the aluminum.

Column A, B, and C contain the material class, material, and material amount set equal to those provided in the same columns in the "Materials Input" worksheet for all materials but the submerged aluminum. Column D then contains density values for the recirculation water and the insulation materials in lbm/ft^3. Column E converts the material volumes to mass (kg) by first multiplying Column C by the density in Column D then dividing by the conversion factor of 2.2046 lbm/kg. The not-submerged aluminum is converted to kg simply by multiplying the Column C mass (lbm) by the conversion factor of 2.2046 lbm/kg. The concrete material amount is input in ft^2, so Column E multiplies the Column C surface area by $1.0058E-5$ kg/ft^2. This number was obtained as described in Section 6.3 from a surface area analysis performed on the tested concrete.

The submerged aluminum surface area and mass in this worksheet are made up of both the submerged aluminum in the "Materials Input" worksheet and a portion of the Interam volume due to its aluminum foil backing. The aluminum submerged surface area in cell C3 is that provided in the previous worksheet plus the Interam volume divided by the measured aluminum thickness (in) of the test sample which is divided by the conversion factor of 12 in/ft.

C3 = Materials Input'!C3+'Materials Input'!C27/(0.398 in / 12 in/ft)

The aluminum submerged mass in cell C4 is that provided in the previous worksheet plus the Interam volume, which is divided by the measured thickness then multiplied by 0.0392 lbm/ft^2 and the conversion factor of 2.2046 lbm/kg to determine the mass of the aluminum foil backing on the Interam in lbm. In order to determine the lbm/ft^2 of the aluminum foil backing, a 1 in^2 piece of the backing was weighed to determine the mass of 0.1234 g. Then the density of this backing is 0.1234 g/in^2 * (144 in^2/ft^2) / 1000 g/kg * 2.2046 lbm/kg = 0.0392 lbm/ft^2.

C4 = 'Materials Input'!C4+('Materials Input'!C27/(0.398/12))*0.0392*2.2046

Finally, the masses calculated within each class are summed in Column F to provide a class total (kg) for each material class tested.

Worksheet = Results Table

This worksheet sums the elemental mass releases calculated for each material on subsequent worksheets and then predicts the amount and type of precipitates which form from the dissolved elements.

Column C calculates the interval duration, i.e., the time (min) between the inputs provided in the "Time Temp pH" worksheet. Cell C2 is the second time provided in the Time Temp pH worksheet minus that given for the time of RCS blowdown.

C2 = 'Time Temp pH Input'!B3-'Time Temp pH Input'!B2

For the next row, cell C3, the interval duration is calculated between the second and third times for which temperature and pH input is given in the Time Temp pH worksheet.

C3 = 'Time Temp pH Input'!B4-'Time Temp pH Input'!B3

This calculation is continued until row 34 where the last time for which temperature and pH input is provided is subtracted by the second to last time.

C34 = 'Time Temp pH Input'!B35-'Time Temp pH Input'!B34

In Column D, the start of the interval is simply set equal to the times given in Column C (hr) of the "Time Temp pH" worksheet which correspond to the times subtracted in calculating the interval duration.

The end of the interval (hr) is calculated in Column E by adding the start of interval time (hr) to the interval duration (min) divided by 60 min/hr.

For Column F, the average pH over each interval is calculated by summing the sump pH values corresponding to the times at the start and end of each interval and then dividing that sum by 2.

F2 = 'Time Temp pH Input'!E3-'Time Temp pH Input'!E2 and

F3 = 'Time Temp pH Input'!E4-'Time Temp pH Input'!E3

Similarly, in Column G the average sump temperature over each interval is calculated by summing the sump temperature values corresponding to the times at the start and end of each interval and then dividing that sum by 2.

G2 = 'Time Temp pH Input'!F3-'Time Temp pH Input'!F2 and

G3 = 'Time Temp pH Input'!F4-'Time Temp pH Input'!F3

Then in Column H the corresponding calcium release over time is summed from the Ca releases determined in subsequent worksheets from calcium silicate, concrete, E-glass, and mineral wool.

H2 = SUM('Ca from CalciumSilicate'!S2,'Ca from Concrete'!S2,'Ca from E glass'!S2,'Ca from Mineral Wool'!S2)

The total calcium mass release calculated in row 34 is the sum released over the 30 days.

Similarly in Column I the silicon release over time is summed from the Si releases determined in subsequent worksheets from calcium silicate, concrete, E-glass, aluminum silicate, mineral wool, and Interam.

I2 = SUM('Si from CalciumSilicate'!S2,'Si from Concrete'!S2,'Si from E glass'!S2,'Si from Al Silicate'!S2,'Si from Mineral Wool'!S2,'Si from Interam'!S2)

The total silicon mass release calculated in row 34 is the total Si released over the 30 days.

In Column J the aluminum release over time is summed from the Al releases determined in subsequent worksheets from the unsubmerged aluminum, the submerged aluminum, concrete, E-glass, aluminum

silicate, and mineral wool. The aluminum foil backing on the Interam is accounted for in the submerged aluminum surface area entered.

J2 = SUM('Al Release by unsubmerged metal'!U2,'Al Release in Sump from Al'!U2,'Al from Concrete'!S2,'Al from E glass'!S2,'Al from Al Silicate'!S2,'Al from Mineral Wool'!S2)

The total aluminum mass release calculated in row 34 is the total Al released over the 30 days.

Next, the precipitate formation is calculated in Columns K-P from the total mass releases determined in Columns H-J. The equations presented in Section 6.4 to determine the quantity of precipitates generated are used.

In Column K, the amount of sodium aluminum silicate precipitate formed is determined. This column contains an if statement that allows the formation of precipitate to be limited by the amount of aluminum if the mass of dissolved silicon is greater than 3.12 times the mass of dissolved aluminum; otherwise, it is limited by the amount of silicon present.

If the silicon mass is greater than 3.12 times the aluminum mass, Column N calculates the amount of sodium aluminum silicate precipitate by multiplying the Column J aluminum release by 9.72. Otherwise, Column O calculates the precipitate amount by multiplying the Column I silicon release by 3.11.

K2 = IF(I2>3.12*J2,N2,O2)

N2 = 9.72*J2 and O2 = 3.11*I2

The total sodium aluminum silicate precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Column L also contains an if statement, which requires the aluminum release to be at least 0.32 times the silicon release for aluminum oxyhydroxide precipitate to form. If the aluminum release is equal to or greater than 0.32 times the silicon release, then the amount of precipitate formed is 2.22 times the difference between the aluminum release and 0.32 times the silicon release.

L2 = IF((J2-0.32*I2)<0,0,2.22*(J2-0.32*I2))

The total aluminum oxyhydroxide precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Column M contains an if statement that sets the amount of calcium phosphate precipitate equal to 0 if no amount is entered for trisodium phosphate in the "Materials Input" worksheet, otherwise, the precipitate is the amount calculated in Column P from the calcium release. Column P calculates the amount of calcium phosphate formed due to the presence of trisodium phosphate by multiplying the Column H calcium release by 2.58.

M2 = IF('Materials Input'!$C$26=0,0,P2) and P2 = 2.58*H2

The calculations above are continued until the last interval duration in row 34. The total calcium phosphate precipitate calculated in row 34 is the total precipitate formed over the 30 days.

Worksheet = Releases by Material

This worksheet simply sums the elemental releases from each material and presents a column chart with this data.

For example, for the E-glass material, the Ca release in Column B is the sum of the Ca interval mass release calculated in the "Ca from E glass" worksheet.

B6 = SUM('Ca from E glass'!R2:R101)

Worksheet = Precipitate by Material

This worksheet determines the relative contributions of each material to the precipitates formed. In order to determine a material's contribution to a precipitate amount, the total amount of the precipitate is multiplied by the ratio of the mass release of the major element which forms the precipitate from that material to the total release of that element from all materials.

For example, for the amount of the calcium phosphate precipitate which may be attributed to the calcium silicate, the sum of the interval calcium mass release in Column R of the "Ca from Calcium Silicate" worksheet is divided by the sum of the total calcium mass release in Column B of the "Releases by Material" worksheet to obtain the ratio. Then this ratio is multiplied by total calcium phosphate precipitate from cell M34 in the "Results Table" worksheet.

B5 = SUM('Ca from CalciumSilicate'!R2:R100)/SUM('Releases by Material'!$B$3:$B$20)*'Results Table'!$M$34

Worksheet = Ca from Calcium Silicate

This worksheet determines the mass release of calcium over time from the calcium silicate amount input in the "Materials Input" worksheet.

The mass of the material (kg) in cell B2 is set equal to that determined for the calcium silicate class in the "Materials Conversions" worksheet (cell F7). Then the mass of the Ca element (kg) is determined in cell B3 by multiplying the calcium silicate mass by 0.345, the fraction of calcium in the nominal calcium silicate formula. The values input in Column B for the constants a-f are given in Table 6.2-1. Constants a, b, and c are used to determine the saturation constant in Equation 6-3, while the d, e, and f constants are used in Equation 6-4 to determine the rate constant.

Columns C-G are the same as those described for the "Results Table" worksheet.

Column H calculates 1000/temperature (K) from the temperatures in Column G. The temperatures in Column G are first converted to Kelvin and then are divided into 1000.

H2 = 1000/((G2-32)*5/9+273.15)

Columns I-K allow for the presence of calcium released from other materials to reduce the release rate of calcium from the calcium silicate material as the release rate is dependent on the total concentration of calcium in solution. This credit is only applied if the sump is assumed to be well mixed on the "Time Temp pH Input" worksheet (e.g., approximately two turnovers of the sump volume after recirculation is initiated).

Column I determines the concentration of calcium at the end of the previous time interval from all the materials by dividing the total mass (kg) of calcium released from Column H of the "Results Table" worksheet" by the coolant mass (kg) from Column E of the "Materials Conversions" worksheet. Then this concentration is divided by 1000000 in order to determine the concentration in ppm.

In the initial time interval, the concentration of calcium released from the previous time interval is 0.

I2 = 0 and I3 = 'Results Table'!H2/'Materials Conversions'!$E$2*1000000

Similarly, Column J calculates the concentration of calcium at the end of the previous time interval from the calcium release from calcium silicate calculated in Column S. The total mass of calcium released in Column S is divided by the coolant mass and 1000000.

J2 = 0 and J3 = S2/'Materials Conversions'!$E$2*1000000

Column K selects whether the concentration of calcium released from all materials or just from the calcium silicate should be used to determine the release rate dependent on whether the option has been selected in Column G of the "Time Temp pH Input" worksheet.

K2 = 0 and K3 = IF('Time Temp pH Input'!G3=1,'Ca from CalciumSilicate'!I3,'Ca from CalciumSilicate'!J3)

Column L calculates the saturation constant using Equation 6-5 from constants a, b, and c, the average interval pH in Column F, and the 1000/T value from Column H.

Saturation constant $(K)=10^{[a + b(pHa) + c(1000/T)]}$ Equation 6-5

L2 = 10^($B$4+$B$5*F2+$B$6*H2)

Column M calculates the rate constant using Equation 6-6 from constants d, e, and f, the average interval pH in Column F, and the 1000/T value from Column H.

Rate constant $(k) =10^{[d + e(pHa) + f(1000/T)]}$ Equation 6-6

M2 = 10^($B$7+$B$8*F2+$B$9*H2)

Column N calculates the release rate using Equation 6-4 from the calcium concentration in Column K (ppm), the saturation constant from Column L, and the rate constant determined in Column M.

Release rate (RR) = kA(1-C/K) Equation 6-4

N2 = M2*(1-K2/L2)

Column O determines whether the release rate calculated in Column N is positive and if so sets the positive release rate (mg/kg-min) equal to that calculated value. Otherwise, the release rate is set equal to 0.

O2 = IF(N2>0,N2,0)

Column P calculates the interval predicted release by multiplying the Column O release rate (mg/kg-min) by the interval duration (min) from Column C and the mass of the calcium silicate (kg) determined in Column F of the "Materials Conversions" worksheet. Then this number is divided by the conversion factor of (1E6 mg/kg) in order to obtain the release in kilograms.

P2 = C2*O2*'Materials Conversions'!$F$7/1000000

Next, in Column Q the amount above the starting mass of material, i.e., the difference between the mass of material released and the mass of the starting material, is determined. In the first row, row 2, the starting mass of calcium from cell B3 is subtracted from the predicted mass release for the first interval. In the second row, the starting mass of calcium is subtracted from the sum of the predicted second interval mass release and the integral mass release from the first interval calculated in Column S.

Q2 = P2-$B$3 and Q3 = (S2+P3)-$B$3

Column R determines the interval mass (kg) of Ca released from the interval predicted mass release and the difference between the mass released and the mass available. If the mass released is less than the mass available, then the interval mass release of Ca is set equal to that calculated in Column P. However, if in an interval more mass is released than is available, i.e., the difference in Column Q is positive, the interval mass released is set equal to the predicted mass release in that interval less the amount of mass predicted to be released above the starting mass.

R2 = IF(Q2<0,P2,P2-Q2)

Finally, in Column S the integral mass release (kg) is determined. For the first interval, the integral mass released is simply set equal to that calculated in Column R for the interval mass release. Beginning with the second interval, the integral mass released is that released in that interval (from Column R) plus the integral mass released determined for the previous interval (from Column S).

S2 = R2 and S3 = R3 + S2

The above calculations are continued until the last interval duration in row 34. The integral mass release calculated in row 34 is the total mass release of Ca (kg) over the 30 day period.

Remaining Worksheets for Insulation Materials

In the remaining worksheets, the same equations are used to determine the Al, Si, and Ca mass releases as in the worksheet for the calcium mass release from calcium silicate. The only differences are in cell B2 which is set equal to the mass of the respective insulation material calculated in the "Materials Conversions" worksheet, cell B3 which multiplies the material mass by the fraction of the element in the nominal material formula, and cells B4-B9 which provide the saturation and rate constants a-f given in Table 6.2-3. However, for concrete cell B3 is set equal to a large number (1000000 kg) because there is no limit to the mass of the exposed concrete surface area.

The worksheets used to determine the aluminum release from the aluminum metal in containment differ from the other insulation materials because a different corrosion model is used.

Worksheet = Al Release in Sump from Al

For the aluminum submerged in the sump, Columns C-H contain the same equations as described in Worksheet = Ca from Calcium Silicate.

Column J squares the pHa value calculated in Column F.

J2 = F2*F2

Column K divides the pHa value in Column F by the 1000/T value in Column H.

K2 = F2/H2

In Column P the log prediction of the aluminum release rate is calculated using the model terms A-E from Columns V and W in Equation 6-2, the Column F pHa values, the Column H 1000/T values, the Column J squared pHa values, and the Column K pHa/(1000/T) values.

$$\text{Release Rate (RR)} = 10^{[A + C(1000/T) + D(pHa)^2 + E(pHa)(T)/1000]} \qquad \text{Equation 6-2}$$

P2 = $W$2+$W$3*F2+$W$4*H2+$W$5*J2+$W$6*K2

Then in Column Q the corrosion rate (mg/m^2-min) is calculated from the term in Column P.

Q2 = 10^P2

Column R calculates the interval release by multiplying the Column Q release rate (mg/m^2-min) by the interval duration (min) from Column C and the mass of the submerged aluminum (lbm) determined in Column C of the "Materials Conversions" worksheet. Then this number is divided by the conversion factor of 10.7639 lbm/m^2 in order to obtain the release in milligrams.

R2 = Q2*C2*'Materials Conversions'!$C$3/10.7639

Column S determines the interval Al release in kilograms by dividing Column R by 1000000 mg/kg.

S2 = R2/1000000

In Column T the integral mass release (kg) is determined. For the first interval, the integral mass released is simply set equal to that calculated in Column S for the interval mass release. Beginning with the second interval, the integral mass released is that released in that interval (from Column S) plus the integral mass released determined for the previous interval (from Column T).

T2 = S2 and T3 = S3 + T2

Finally, in Column U the integral aluminum mass release is limited to the mass available. If the integral mass release calculated in Column T is less than the total submerged aluminum mass determined in the "Materials Conversions" worksheet, then the mass available integral mass release in Column U is set equal to that calculated in Column T. Otherwise, the Column U mass release is set equal to the total mass available for release.

U2 = IF(T2<'Materials Conversions'!$E$4,T2,'Materials Conversions'!$E$4)

The above calculations continue until the last interval duration in row 34. The integral mass release calculated in cell U34 is the total mass release of Al (kg) from the submerged aluminum over the 30 day period.

Worksheet = Al Release by Unsubmerged Metal

For the aluminum exposed to the spray, Columns C-H contain the same equations as described in <u>Worksheet = Ca from Calcium Silicate</u> except the average pH and average temperature are determined from the pH and temperature profiles input in the "Time Temp pH" worksheet for the spray solution instead of for the sump.

The remaining columns are the same as those described in <u>Worksheet = Al Release in Sump from Al</u> except for Column R.

Column R calculates the interval release if a spray pH value is entered in Column H of the "Time Temp pH Input" worksheet. Otherwise, the interval release is 0 because the containment spray has been terminated. The interval release is determined by multiplying the Column Q release rate (mg/m^2-min) by the interval duration (min) from Column C and the mass of the submerged aluminum (lbm) determined in Column C of the "Materials Conversions" worksheet. Then this number is divided by the conversion factor of 10.7639 lbm/m^2 in order to obtain the release in milligrams.

R2 = IF('Time Temp pH Input'!H3>0,Q2*C2*'Materials Input'!$C$5/10.7639,0)

The above calculations continue until the last interval duration in row 34. The integral mass release calculated in cell U34 is the total mass release of Al (kg) from the unsubmerged aluminum exposed to the containment spray over the 30 day period.

Worksheet = All Aluminum Release with Plot

This worksheet compares the aluminum release over time from the submerged aluminum and the aluminum exposed to the spray.

Column C is set equal to the end of the time duration in Column E of the "Al Release in Sump from Al" worksheet.

C2 = 'Al Release in Sump from Al'!E2

Column B converts this time into minutes by multiplying by 60 min/hr.

B2 = C2*60

Column D is set equal to the integral aluminum release from the submerged aluminum.

D2 = 'Al Release in Sump from Al'!U2

Column E is set equal to the integral aluminum release from the aluminum exposed to the spray.

E2 = 'Al Release by unsubmerged metal'!U2

Column F calculates the total aluminum release by summing the aluminum submerged release in Column D and the unsubmerged aluminum release in Column E.

F2 = D2+E2

Finally, the values in Columns D-F are plotted against the time in Column C.